PSEUDOLITE ARCHITECTURE AND PERFORMANCE ANALYSIS FOR THE FAA'S NextGen AIRSPACE

THESIS

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AFIT-ENV-13-M-07

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Captain, USAF

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Abstract

By 2025 the FAA plans to have fully implemented its NextGen Airspace design. NextGen takes advantage of modern positioning technologies as well as automation, data sharing, and display technologies that will allow more efficient use of our ever busier National Airspace (NAS). A key element of NextGen is the transition from surveillance RADAR providing aircraft separation and navigation to the use of the GPS and Automatic Dependent Surveillance Broadcast (ADS-B). ADS-B couples the precision of the GPS with networked ground and airborne receivers to provide precise situational awareness to pilots and controllers. The result is increased safety, capacity, and access with reduced reliance on an outdated and costly existing infrastructure. Reliance on the vulnerable GPS requires a backup system with higher positioning accuracy than those that are in place today. The USAF 746th Test Squadron at Holloman AFB, in partnership with Locata Corp., has demonstrated an Ultra High Accuracy Reference System (UHARS) over the Holloman Range composed of pseudolites (ground based satellites) transmitting GPS like signals. This study evaluates the suitability of the UHARS when applied on a national scale to meet Alternate Precision Navigation and Timing (APNT) requirements. From a systems architecture perspective UHARS is evaluated against APNT CONOPs stated Operational Improvements and Scenarios. From a signal architecture perspective the UHARS is evaluated against frequency and bandwidth constraints, service volume requirements and positioning accuracy determined by NextGen Airspace aircraft separation criteria.

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PSEUDOLITE ARCHITECTURE AND PERFORMANCE ANALYSIS
FOR THE FAA'S NextGen AIRSPACE

I. Introduction

Background

By 2025 the FAA expects to have implemented many of its Next Generation (NextGen) improvements to the National Airspace (NAS). NextGen Airspace boasts improvements to nearly every facet of the NAS, including efficiency, safety, situational awareness, environmental impact, and cost of service. A key component of NextGen in 2025 is the transition from legacy navigation systems and RADAR surveillance to Alternate Precision Navigation and Timing (APNT) and Automatic Dependent Surveillance Broadcast (ADS-B) (Federal Aviation Administration 2012).

Today's NAS architecture dictates that Air Traffic Control (ATC) determines an aircraft's position based on Surveillance RADAR returns. The precision of this method degrades with increasing range from the RADAR site and is a factor in the minimum separation provided between aircraft for safety. In a non-RADAR environment aircrew must report their position as determined from GPS or navigation aids such as VOR and DME. This is known as procedural separation and it is the least accurate, therefore requiring the greatest separation between aircraft.

The transition to ADS-B in NextGen architecture is dependent on precise aircraft reported position rather than surveillance or primary RADAR. GPS is currently the only navigation source approved for ADS-B with the accuracy required to meet

NextGen performance objectives. One of the primary objectives of NextGen is to increase capacity and access to our busiest airports. Precise navigation and reduced separation in busy airspace (more aircraft flying efficiently through a smaller area) are the enablers. A secondary objective of dependent surveillance is a reduction in the required infrastructure and maintenance cost of the current NAS architecture. This means removing non-essential and aging RADAR sites and navigation aids. Combined, the plans to reduce separation minimums and eliminate existing infrastructure place a heavy burden on the GPS service. The safety of life concern and demand for high availability with few outages will require a backup to the vulnerable GPS. This secondary navigation source is known as APNT.

The APNT CONOPS is our primary source of information regarding the necessary capabilities and functions of any APNT solution. This CONOPS outlines multiple scenarios in which degraded or denied GPS will have significant impact on the safety, efficiency, and capacity of NextGen airspace in 2025. At best, user workload is increased and fuel or time savings from efficient routings is lost. At worst, reduced separation minimums that were sufficient in the presence of GPS would place large numbers of aircraft dangerously close to one another around dozens of the nation's busiest airports. The ideal form of APNT would provide a seamless transition from GPS with no degradation in performance and unnoticed by the users.

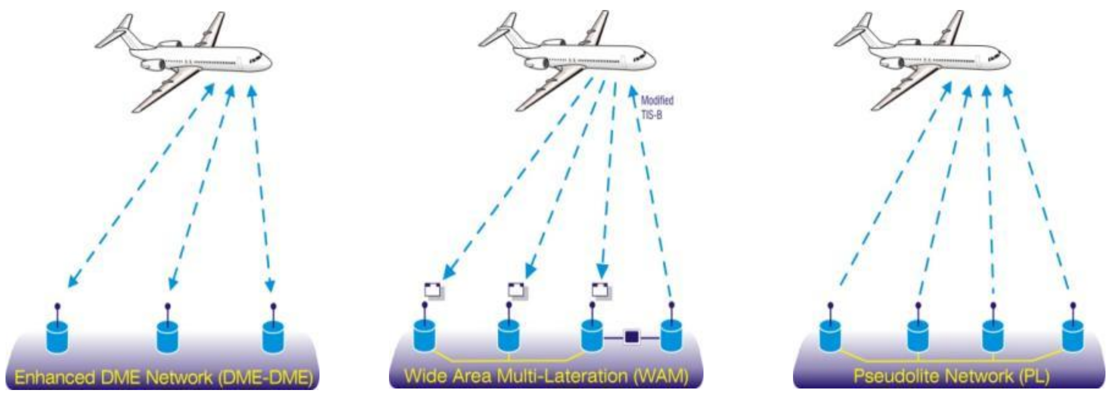

Figure 1: APNT Architecture Alternatives

Three forms of APNT are being considered by the FAA and are depicted in Figure 1. The first is an improvement of existing Distance Measuring Equipment (DME). With DME, range from a known ground site is determined by timing a round trip signal sent from an aircraft to the ground site and back. An "interrogation" is sent from the aircraft at a specific frequency in the form a pulse-pair. If a ground site on the same frequency receives the pulse-pair it responds in kind after a specified delay. The round trip time, plus the delay, is computed by the aircraft and converted to range. Given a range to two sites, and some knowledge of altitude, heading and airspeed, a "DME-DME" navigation system can determine an aircraft's position. DME ground sites have a limited capacity and can become saturated in busy airspace. Current DME performance would not provide the accuracy or availability required by the APNT CONOPs.

The second form of APNT being considered is Multi-Lateration (MLAT). An aircraft's position is determined again by measuring distances to multiple ground sites but the computation is done on the ground. Ranging methods vary but each method results in a unique range known to each ground site. The range to each site is combined over a data network and used to compute a position in space. The aircraft's position is then sent via wireless data link to the aircraft. MLAT already exists on the ground at busy airports to monitor busy traffic on ramps, taxiways, and runways (FAA 2007). One downside of MLAT is that information about range to an aircraft must be compared by multiple ground MLAT sites. This requires network infrastructure and could theoretically be saturated. A second downside is the increased risk to integrity as data passes through the network and position is transmitted to the aircraft.

The third form of APNT being considered is a pseudolite architecture. Pseudo-satellites perform functions similar to those of Satellites of the GPS but exist on the ground as fixed transmitters. The candidate technology that will be evaluated in this thesis, known as Locata, was developed on modified GPS hardware and resembles GPS signal architecture in several ways. Each pseudolite transmits a unique signal that is synchronized to a common clock. Avionics on the aircraft compare the time of reception of a signal to the time of transmission to compute range to the pseudolite. Computed range to multiple pseudolites is used to determine position. Capacity of a pseudolite architecture is unlimited. Integrity of the computed position is a composite of each of the signals used for the calculation. Like GPS, a broken or false signal could be identified by the user autonomously, although at a cost. A significant challenge of pseudolites is synchronization of their clocks on a continental scale. Methods of synchronization will be explored further in this thesis.

The 746th Test Squadron at Holloman Air Force Base has successfully demonstrated a pseudolite network known as the Ultra High Accuracy Reference System (UHARS) to accuracies that far exceed APNT requirements. The purpose of the UHARS is to provide a reference system in the absence of GPS on the White Sands Missile Range accurate to 10 cm (Craig 2011). It is based on the local area pseudolite technology known as Locata. Locata signals are very similar to GPS signals in many regards. Changes have been made to transmitted power levels, Time Domain Multiple Access (TDMA) schemes, and almanac information encoded in the signals to account for the terrestrial environment of the pseudolites compared to their GPS counterparts. Locata is billed as an alternative to GPS in environments that would deny the use of GPS such as inside warehouses or in deep urban canyons and open pit mines. The UHARS demonstration is an adaptation of Locata that allows signal tracking up to 30 nautical miles. In October 2011 ten pseudolites like the one depicted in Figure 2 were deployed over 800 square miles of the White Sands Range as a demonstration. The operational UHARS will cover more than 2500 sq. miles (Craig 2011).

Figure 2: UHARS Pseudolite at White Sands

The FAA APNT team has stated their desire to determine NextGen's APNT source by 2015. This study piece of the larger effort to determine what form of APNT will best serve our needs of 2025 and beyond.

Problem Statement

How can the UHARS model of Locata pseudolite technology be applied to meet the APNT problem of NextGen 2025?

The 746th Test Squadron and Locata Corporation have together demonstrated that the UHARS can meet or exceed APNT accuracy requirements over a small area with good line-of-sight topography between pseudolites. The APNT CONOPS demands a positioning source that is available over all of the Continental United States, (CONUS) at altitudes and through corridors used to access the nation's busiest 135 airports.

Methodology and Research Objective

This thesis will consider the application of pseudolites to the APNT problem in two distinct phases. The first phase will develop Systems Engineering architecture as a baseline that is modeled after the DoD Architecture Framework (DoD CIO 2010). The architecture will describe a pseudolite navigation system in the context of the FAAs approved APNT CONOPs. The focus of this architecture will be primarily on pseudolites, other organizations have been tasked with developing architecture for other alternatives such as DME/DME and MLAT techniques. Viewpoints will be generated beginning with high level operational views that are consistent with existing documentation of NextGen 2025. These views will, for the most part, be technology agnostic and could describe any pseudolite system in the context of the APNT CONOPS. The primary objective of the operational viewpoints is to connect the scenarios and operational improvements outlined in the APNT CONOPS with the theoretical capabilities of a pseudolite architecture.

Systems views will then be developed that are more specific to the UHARS. Systems views will illustrate connectivity between nodes of the UHARS network and ultimately highlight the greatest challenge posed by a nationwide pseudolite network based off of UHARS. The systems views will show the UHARS as it has been implemented at Holloman AFB and then be modified to show a potential variation of the UHARS that could satisfy the APNT need.

An enterprise architecture exists for As-Is and To-Be NextGen airspace in an incomplete form. The architecture focuses on how NextGen will function in the presence of GPS. This study will highlight the strengths and shortcomings of a pseudolite solution in the context of the NextGen framework.

The second part of this thesis is a model of the UHARS signal that is designed to predict performance of a pseudolite system of varied configurations. The model incorporates many characteristics of the UHARS signal as variables, applies basic models of signal propagation, hardware attenuation, and receiver performance to predict the positioning accuracy of the signal. The model also considers signals that will potentially share the same band as the new APNT signal. These signals reside in a protected band from 960 MHz to 1215 MHz known as the Airborne Radio Navigation Service (ARNS). Each “resident” of the ARNS has its own published values of acceptable interference that must be considered. Three primary characteristics of any signal become apparent. The effective range of the signal will determine the number of pseudolites required to cover the NAS and 135 busy airports. The coded message within the signal will affect its theoretical accuracy and precision. The combination of power and signal frequency and encoding will affect its influence on (and from) radios in nearby channels.

The objective of this signal model is to bound the trade space between positioning performance of the system, the potential cost of infrastructure required for nationwide coverage, and its ability to coexist with existing radio navigation systems.

Investigative Questions

To meet the research objectives stated above, the following questions will be used as guidelines in the production of architectural viewpoints and building a model of pseudolite APNT.

- What measures of performance will adequately define any APNT system within the context of NextGen2025?
- What is the cost of increasing coverage within the continental US (CONUS) or providing an over-determined solution for integrity in terms of the number of pseudolites required?
- How does the service volume of a pseudolite affect the number of pseudolites required to cover all airspace requiring APNT?
- How will a pseudolite APNT signal operate within the ARNS band?
- Can the UHARS meet the operational improvements of NextGen and scenario based CONOPS of APNT, what levels of performance will be required in any given airspace?
- What are the shortfalls of the UHARS signal, pseudolite architecture, and APNT performance requirements when applied to NextGen 2025 operational improvements?
- What is an acceptable means of clock synchronization?

Assumptions, Limitations and Scope

This thesis is written in the context of NextGen 2025 improvements to the NAS. The focus is on pseudolite technology applied to the need for APNT. The APNT CONOPs is the primary reference that defines the mission of APNT (Federal Aviation Administration 2012). The pseudolite architecture proposed reflects the minimum "threshold" performance stated by the FAAs APNT team, as well as the desired level of performance.

This thesis will not attempt to model the cost of any proposed pseudolite APNT solution. It will provide a foundation upon which cost estimates could be developed in the future. Answers to questions such as: 'How many pseudolites will be required?' and 'What timing infrastructure will be needed?', will be discussed in this thesis.

This thesis will not evaluate the performance of a pseudolite signal outside of US airspace. However, existing navigation sources in the ARNS band are protected by international treaty and any APNT solution would be equipped on aircraft that fly internationally. Logically then, future research should include suitability in oceanic or foreign airspace.

Key assumptions are as follows:

- Aircraft operating in 2025 controlled airspace will be required to operate ADS-B equipment coupled to a suitable navigation source.
- GPS outages may be caused by unexpected system failures, planned or predictable interference, or by malicious jamming and spoofing activity.

- At a minimum, APNT must provide means of safe navigation to a point clear of GPS outage or to an instrument landing system (ILS) final approach fix at one of the nation's 65 busiest airports.

In the development of the UHARS signal model many assumptions were made about the performance of receivers, masks and filters, and the stated properties of other ARNS navigation signals. Signal propagation, range accuracy, and other error models are only rudimentary models. Therefore, the signal model is limited to first order analysis of pseudolites and the UHARS as an APNT solution. Future research should include high fidelity simulation or actual hardware implantation of a proposed APNT signal.

II. Literature Review

The following review covers those documents and topics that were key to this thesis. They each provide an important volume of background information required to develop the architecture and signal models that follow. Minor documents not covered in this section are referenced throughout the text.

Concept of Operations

The United States' air transportation system is under increasing stress from user demands. While accommodating increasing traffic it must also accommodate increasing environmental and security concerns. The current system is probably not capable of meeting our demands beyond 2025. In response the Joint Planning and Development Office has been tasked with defining the CONOPS for the Next Generation Air Transportation System (NextGen) (Joint Planning and Development Office 2010).

NextGen boasts several improvements over today's air transportation system. These improvements can be divided into services such as Air Traffic Management, Airport Operations, Net-Centric Infrastructure, and Safety Management. Communications and automation will play a big role in NextGen architecture, allowing service providers and customers to share information and respond accordingly, known as Shared Situational Awareness (SSA).

Of note, NextGen must accommodate a predicted 100% increase in air traffic by 2025. While increasing capacity, there will always be a desire to reduce delays and interruptions, reduce operator workload, decrease environmental impact, and improve safety. NextGen addresses all of these issues by relying on modern enabling technologies that did not exist when the present air transportation system was designed. Increasing capacity, improving safety and efficiency, and reducing interruptions means squeezing more aircraft into the same airspace; this means higher precision means of navigation and surveillance. The key enabling technology to increase traffic density was the Global Positioning System, other Global Navigation Satellite Systems (GNSS) and ground systems collectively known as Precision Navigation and Timing (PNT).

A transition to PNT and SSA will not only provide the benefits listed above but allow the FAA to eliminate costly legacy navigation and surveillance systems.   PNT alone allows aircraft operators to determine their position in time and space more precisely than with traditional VOR and DME equipment. Through SSA, controllers on the ground are able to use PNT to support more precise surveillance of air traffic, thereby reducing traffic separation minimums and optimizing traffic flows. This is known as dependent surveillance (surveillance depends upon aircraft reported position) and leads us to a common failure mode that had not existed in the past. When PNT is lost, ATC surveillance capability is lost as well. Current surveillance RADAR performance is not able to support NextGen standards.

The APNT CONOPS provides a brief background of NextGen improvements and places the need for APNT into context. The CONOPS describes the bona fide need for an alternate positioning source, builds two scenarios in which users of NextGen would require an APNT source, and then outlines the impacts of GPS interference on the NAS without an APNT source (Federal Aviation Administration 2012).

Because air transportation navigation and surveillance are "safety-of-life" operations, the reliance of both on PNT requires an alternate system be in place. National Policy directives mandate that the Department of Transportation and Department of Homeland Security work together to mitigate the threats posed to national infrastructure that could cause harm to citizens or disrupt economies as well as provide a backup to the GPS in case of a disruption (Federal Aviation Administration 2012). As stated above, current surveillance and navigation infrastructure could not serve as a backup because it lacks the precision. As transition to NextGen progresses and reliance on PNT becomes greater the potential cost of a GPS outage grows. With a backup in place, the value of GPS as a terrorist target would also be diminished. Accordingly, four pillars of APNT are outlined in the APNT CONOPS:

- Safe recovery (landing) of aircraft flying in Instrument Meteorological Conditions (IMC) under Instrument Flight Rule (IFR) operations
- Strategic modification of flight trajectories to avoid areas of interference and manage demand within the interference area
- Continued dispatch of air carrier operations to deny an economic target for an intentional jammer
- Flight operations continue without a significant increase in workload for either the pilot or the Air Navigation Service Provider (ANSP) during an interference event.

The two scenarios developed in the APNT CONOPS describe a commercial carrier and a general aviation aircraft conducting long range flights into Bozeman, MT and Miami, FL. At each stage of flight, from pre-flight planning to post-flight shut down at the terminal, the operational impacts of a GPS outage in the absence of an APNT source are highlighted. The impacts of a GPS outage and the response by ATC and operators will vary depending on the nature of the outage. Many forms of GPS outage or interference are described and can be categorized by a few variables. Is the outage planned, can it be predicted, or is it unpredictable? Is the outage localized or wide spread? Is the outage intermittent or continuous? Realistic GPS interference scenarios are presented in two forms. "Personal privacy devices" are localized, intermittent, and unpredictable. These are low powered noise jammers often used to disable tracking devices on vehicles. Intentional GPS jamming for National Security can be widespread but is planned and predictable. Intentional interference with GPS by the DOD is often necessary for the development of advanced navigation technologies.

Finally, the APNT CONOPS references positioning performance standards for various types of airspace and phases of flight and defines "APNT Zones" that would be used to define required performance levels of any APNT signal within each Zone. This thesis will reduce the performance criteria to the basic performance standards of APNT and identify which Operational Improvements will be met by a pseudolite APNT system.

Locata Pseudolites

Locata technology provides the basis for the pseudolite model being studied in this thesis. Locata was developed for commercial use by an Australian company to provide a PNT source in environments that would preclude the use of GPS. Such environments include open pit mining, urban canyons, warehouses, or in other buildings with poor GPS signal. To simplify the development process, the Locata positioning signal was modeled after the GPS and then modified to meet the unique requirements of a terrestrial positioning system (Locata Corporation 2011).

A LocataNet is built from multiple ground based pseudolites, each referred to as LocataLites, which make up the Terestrial Segment (TS), and a limitless number of user receivers known as the User Segment (US). There is no distinct control segment as with the GPS. Establishing the TS involves surveying each LocataLite position. Because the LocataLites are in a fixed position no control segment is required to monitor the position of the LocataLites. LocataLites autonomously arrange themselves into the appropriate network patterns based on available line-of-site geometry over the network area. This line-of-site link between LocataLites became one of its primary limitations when applied to nationwide APNT.

As a pseudolite positioning system, Locata uses multiple ranging signals from known points to determine a user's position in space. Most readers will be at least partly familiar with this method of positioning used by the GPS. The primary difference between GPS, or other global navigation satellite system (GNSS), and Locata is that the ranging signals are sent from ground based "pseudo satellites" rather than space based satellites. The timing of the ranging signals from each pseudolite is predefined. Through the use of pseudorandom spreading codes, much like the GPS, this time of transmission is compared to the time of reception at the user's receiver to determine the distance the signal has traveled. This process does not require a precise clock in the user's receiver but does require coordinated time references at each of the pseudolites. GPS takes advantage of precise clocks and correction updates from the GPS control segment. LocataNets use a proprietary process known as TimeLoc.

TimeLoc is a method of referencing each LocataLite's internal clock to a master LocataLite. The master LocataLite's time reference may be its own internal clock, or more precise references derived externally. This eliminates the need to include clock correction information in the ephemeris data of the signal. To synchronize a slave to the master, the slave LocataLite "listens" to its own transmitted signal and matches it, in phase, to the received signal from the master LocataLite. A single "hop" is said to be accurate to 6 cycles, 2 nano-seconds, or 60 centimeters (Locata Corporation 2011). TimeLoc can then be cascaded such that a slave LocataLite is a master to a third LocataLite beyond line-of-site from the original master. This method of time synchronization is precise and low cost but requires a clear line-of-site from one LocataLite to another.

Satellites in the GPS constellation are over 20,000km away, with a variation of only a few thousand kilometers. Terrestrial pseudolites of LocataNets may range from tens of kilometers to only a few meters. The resulting variation in signal strength can easily exceed the dynamic range of Locata receivers derived from the pseudorandom spreading codes' code division multiple access (CDMA). The solution is to include a TDMA scheme, on top of the CDMA, into the Locata signal. Each LocataLite is assigned a position on a sub-net that allows it to broadcast only 100msec of each second. This prevents interference between LocataLites that may be near and far. The TDMA scheme will be explained in greater detail in Chapter 4.

To allow an elegant combination of GPS and Locata hardware, Locata designers built upon the GPS frequency plan. The pseudorandom codes of each LocataLite are the same codes used by GPS, although "chipped" at a ten-times faster rate to improve ranging precision and spread the signal over a wider bandwidth. The base oscillator frequency is the same, although Locata transmits in the license-free 2.4GHz ISM band. Modifications in this thesis will attempt to keep these similarities intact.

To mitigate multi-path interference, and enable "wide-lane" carrier phase techniques, each LocataLite transmits two similar signals on different frequencies (Locata Corporation 2011). Antenna spatial diversity can also be implemented at a LocataLite to mitigate multi-path. Transmission of two signals from two physically separated antennas requires four unique signals from each LocataLite. These techniques of multipath mitigation are important in the typical Locata installation indoors, in open mines, and in urban areas. These crowded spaces offer many opportunities for signals to reflect off of objects.

Ultra High Accuracy Reference System

The Air Force's 746th Test Squadron, based at Holloman AFB, NM, is the Department of Defense's lead test organization for GPS user equipment and other navigation references systems. To evaluate the performance of user equipment in the presence of GPS interference, or to develop new technologies capable of meeting user navigational needs in the absence of GPS, the 746th required a non-GPS based positioning system (NGBPS). This precise NGBPS would be used as a "truth" reference in the course of test and evaluation over the White Sands Missile Range and is referred to as the Ultra High Accuracy Reference System (UHARS).

The 746th Test Squadron chose to adapt Locata technology to meet its UHARS requirements based on Locata's demonstrated successes (Craig 2011). Prior to 2010 Locata had been successfully demonstrated for commercial application in mining and indoor warehouse automation to centimeter level accuracy (Barnes 2005). The UHARS would require performance over much wider areas, tracking maneuvering aircraft at over 500km/hr. Locata was contracted to update their technology and demonstrate the following enhancements:

- Locata Receivers must acquire and track signals at a minimum range of 30 miles
- Nanosecond level "TimeLoc" synchronization of LocataLites at these ranges
- Transmit Locata signals at higher power via external amplifier while maintaining signal and TimeLoc integrity
- Design and apply transmitter and receiver antennas to provide adequate gain and multipath mitigation under aircraft dynamics
- Demonstrate adequate receiver tracking loop performance under aircraft dynamics
- Develop tropospheric models that mitigate large errors experienced by terrestrial signals propagated over long ranges
- Ensure post-processed accuracy better than 18cm 3D-RMS (PDOP<3) at long range

To meet these challenges Locata focused on four key enhancements. First, the range of each LocataLite signal had to be increased from approximately 10km to over

50km. A suitable external amplifier was chosen to increase transmitted power from 100 milliwatts to 10 watts. Second, to achieve a 3D solution at altitude, antennas with suitable gain patterns had to be developed to reach LocataLites directly below aircraft as well as near the horizon. Third, the LocataLite receivers had to demonstrate the ability to track signals from banking and maneuvering aircraft. The expected range and acceleration rates had to be simulated on the ground and tracked prior to demonstration at White Sands. Fourth, the errors induced by propagating a signal through 30 miles of the troposphere had to be appropriately modeled and removed.   Through accurate modeling, and metrological data gathering in real time this error was reduced from approximately 280 parts per million (about 13.5 meters at 30 miles) to only a few parts per million, or 4.5 centimeters.

In October of 2011, a scaled UHARS was demonstrated on the White Sands Missile Range in an area of approximately 35km by 30km.   The network, shown in Figure 3, was made up of ten LocataLites synchronized via TimeLoc hops of up to 7 miles. The primary master LocataLite was positioned on a mountain top which provided a clear line-of-sight to all but one of the LocataLites.   This stranded LocataLite was successfully included in the network via a single "hop" to the master. Throughout testing, the UHARS network was able to maintain nano-second level timing synchronization after approximately 30 seconds of initialization time. During the demonstration an Air Force C-12 was flown with a Locata receiver as well as a GPS receiver and inertial reference unit to collect truth data for post processing.

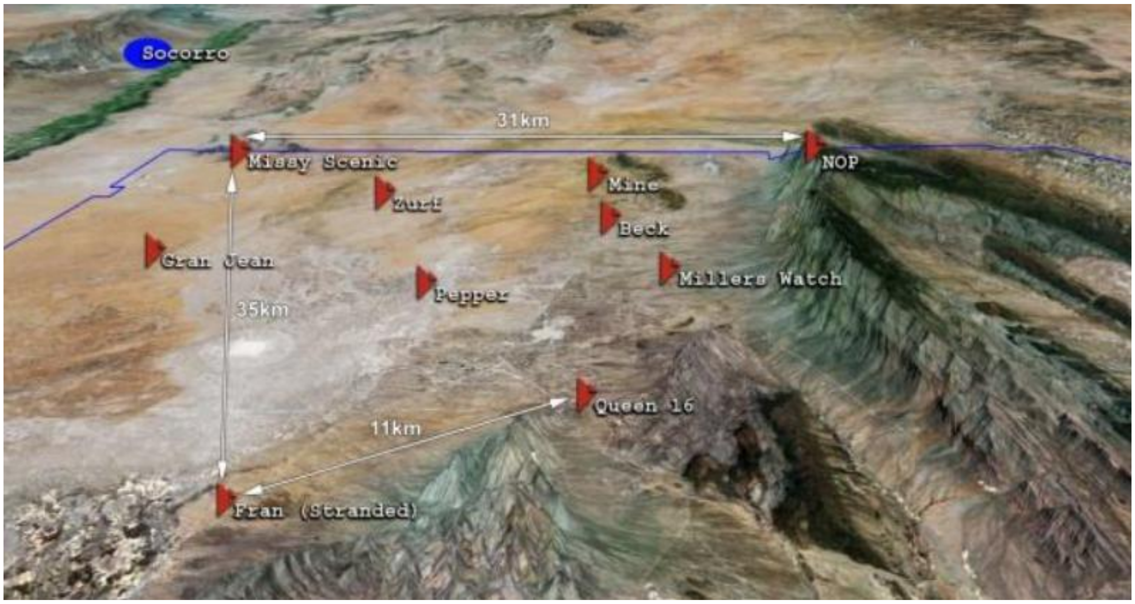

Figure 3: UHARS Pseudolote Network

Transmitting at 10 watts allowed the test aircraft to acquire the UHARS signal at a range of 62km. Once acquired, signals were tracked at a range of 66km. Recall, the 746th's minimum range to acquire and track was 48km. During the flight test data was collected in a race track pattern at 195kts, 25,000ft above sea level. Range to a typical LocataLite varied from approximately 25km to 35km during the bulk of the test. This provided received signal strength from approximately -95dBm to -100dBm. These values will be used as a reference when predicting performance of an APNT system built on a national scale.

The data gathered during flight testing showed that the UHARS system met the 746th Test Squadrons accuracy requirements. Tracking all 10 LocataLites, the Positional-Dilution of Precision (PDOP) averaged 2.35, with a worst case of 3. The vertical dilution was the largest contributor to DOP at an average of 2.06. Given a

PDOP of less than 3, the 746th required a positioning accuracy of 18cm or better. The Locata UHARS system was able to demonstrate a carrier solution RMS accuracy of 17.4cm. A more robust code based solution provided 24.5cm 3 dimensional RMS accuracy.

Based on its performance when applied to the UHARS, Locata technology could be a good candidate for a nationwide APNT system. This thesis will evaluate how a pseudolite system meets NextGen APNT requirements from an operational standpoint and it will also evaluate how the UHARS could be modified to meet performance requirements. The primary challenge of adapting the UHARS to APNT is scale.

ADS-B

Automatic Dependent Surveillance - Broadcast (ADS-B) is one of the primary improvements in NextGen architecture. ADS-B will allow the FAA to transition the air traffic control system from primarily using ground based RADAR to primarily using precise positioning sources such as Wide Area Augmentation System (WAAS) enabled GPS. NAS surveillance will be “dependent” upon aircraft reported position by 2025. The transition to ADS-B has many operational benefits, including decreased separation minimums between aircraft, air-to-air surveillance for increased safety and awareness, and more efficient use of resources as legacy surveillance and navigation infrastructure is decommissioned.

All aircraft operating in controller airspace are required to transmit an ADS-B Out signal prior to 2020. (Federal Aviation Administration 2010). This ADS-B out signal has many components but consists primarily of the aircrafts position, altitude, and velocity information, as well as unique aircraft identification information. The ADS-B Out messages broadcast from nearly every aircraft in the NAS are received by Ground Based Transceivers (GBT) and combined to build a picture of airborne traffic. This information is then delivered to air traffic controllers and re-broadcast to aircraft equipped with ADS-B In equipment. In this fashion, both aircrew and air traffic controllers will have the same, precise, near real time situational picture of the NAS. ADS-B In is not yet a requirement at any point in the future, therefore, aircraft without this capability will rely on visual separation and ATC guidance for separation.

ADS-B Out messages will be transmitted on one (or both) of two signals. Above 18,000' MSL, all aircraft must transmit on what is known as "1090 Extended Squitter". 1090ES is a 1Mbps message encoded on a 1090 MHz carrier wave (Radio Technical Commission for Aeronautics, SC-186 2006). Below 18,000' MSL aircraft operators will have the option to transmit ADS-B Out through a Universal Access Transceiver (UAT) in 1Mbps messages encoded on 978 MHz carrier channel (Radio Technical Commission for Aeronautics, SC-186 2009) s. The ADS-B Out information is received by ATC on the ground or by ADS-B In and TCAS equipped aircraft in the air. What is important to note, again, is that in the absence of surveillance RADAR and in congested airspace, surveillance relies on precise position information broadcast via

ADS-B. The dissemination of surveillance information via ADS-B In and ADS-Rebroadcast (ADS-R) is beyond the scope of this thesis.

ARNS Band Users

A constraint placed on any potential APNT system is that it must operate within the Aeronautical Radio Navigation Service (ARNS) band. This band spans from 960 MHz to 1215 MHz and is protected not only by the FCC but by international treaty (CFR Title 47, Part 87 2012). Although the band is ideal for an APNT signal because of the protection and monitoring it is afforded, it is a very "crowded" band. The systems that currently utilize channels within the band span from end to end, some on hundreds of narrow channels, others on a single wide-band channel.

As mentioned above, ADS-B Out information will be transmitted via the UAT. UATs will also be used to transmit and receive Traffic Information Service (TIS-B), and Flight Information Service (FIS-B). Delivering this information to the cockpit is a major enabling capability of NextGen operational improvements. TIS-B and FIS-B are means of delivering information about nearby aircraft, and flight planning information such as airspace restrictions, hazardous weather reports, and weather imagery.

The UAT signal is centered on 978 MHz and modulated using continuous phase, frequency shift keying (CPFSK). Because the UATs will be numerous and channel saturation is a potential hazard, the signal is "spread" using a Time Domain Multiple Access technique. This TDMA scheme minimizes the effect of UAT signals on adjacent channels while allowing many simultaneous co-channel operators. The UAT TDMA frame is one second long. Ground stations will be assigned fixed message start opportunities (MSOs) within the first 176 msec of each frame. Airborne UATs transmit on pseudo randomly varying MSOs within the latter 800 msec of each frame. This ensures that no ground UATs will interfere with another ground UAT, and airborne interference will be intermittent and unlikely to occur in consecutive frames (Radio Technical Commission for Aeronautics, SC-186 2009).

Distance Measuring Equipment (DME) is used to determine range from fixed ground stations. Airborne transceivers "interrogate" the ground station on a channel unique to that ground station. The ground station replies on an associated, but offset by 63 MHz, channel after a brief delay. The time required to receive the reply at the aircraft is used to determine range. The interrogation and reply signals are made up of brief pulses spaced at fixed intervals. This intermittent nature of the signal has allowed other ARNS systems to use the same frequencies as DME on a non-interference basis. DME occupies narrow channels spaced at 1 MHz from 962 MHz to 1215 MHz (FAA 1984). A few of these channels are in limited use because of their proximity to other ARNS signals or their application, as in the case of mobile TACAN (MILSTD-291C 1998).

DME signals are often associated with other navigation signals such as TACAN, VOR, and ILS (CFR Title 47, Part 87 2012). The channel pairings between DME interrogation, DME reply and these associated systems are often fixed and published. Therefore, if an APNT source might interfere with these DME channels, consideration must be given to the effects on the associated systems. This will be discussed in greater detail in Chapter IV.

The Air Traffic Control RADAR Beacon Service (ATCRBS) occupies two wide bands of the ARNS band. The ATCRBS is the only means of surveillance today, and although a few transmitters will be decommissioned as ADS-B becomes operational, this band is not likely to become available anytime soon. Ground based surveillance RADAR and transponder interrogation signals are transmitted at 1030 MHz. The reply signals from airborne transponders are centered on 1090 MHz. These signals are high powered and may carry modulated data at rates of up to 1 Mbps (RTCA 2008). For this reason DME and TACAN channels within approximately 10 MHz of 1030 MHz or 1090 MHz are not in common usage. Other ARNS systems have made similar compromises to avoid interference with the ATCRBS.

The Joint Tactical Information Distribution System (JTIDS) is, as the name suggests, a data-link used in the United States and by our allies for military purposes. The JTIDS signal allows secure communication between many types of vehicles and hand held devices. The JTIDS signal was placed in the ARNS band on a non-interference basis. To meet this requirement the JTIDS uses a TDMA scheme to spread its energy over the ARNS band.

The JTIDS occupies 51 channels between 969 MHz and 1206 MHz. The channels are spaced approximately 3 MHz apart and there are notable gaps from 1008-1053 MHz and 1065-1113 MHz. These gaps prevent interference with ATCRBS. The TDMA architecture provides message start opportunities spaced approximately 8 msec apart. The low duty cycle and message pulse signature prevents interference with any particular DME or TACAN channel (DoD 2012).

As part of its GPS modernization effort, the DOD has added an additional navigation signal to newer GPS satellites. The signal, referred to as L5, is an open signal for civilian use in the ARNS band. It is intended to be a more reliable signal and add redundancy for use in safety of life applications. The first satellite to broadcast an L5 signal was launched in 2010. This L5 signal is centered on 1176 MHz and is modulated similarly to the GPS L1 and L2 signals, although at a much faster chipping rate. The 10.23 MHz chipping rate spreads the L5 signal over approximately 20 MHz (GPS Directorate 2011). Because the energy of the signal is spread over a wide band, is modulated by binary phase shift keying (BPSK), and is received at low power levels by the user, it is able to share the ARNS band with multiple DME and TACAN channels.

The European Space Agency is currently launching its own form of GNSS, known as Galileo. By the end of 2013, six of thirty planned satellites will have been launched. Each current Galileo satellite will broadcast several navigation signals, the E5 signal will reside in the ARNS band. The E5 signal is modulated using CDM like the GPS but is modulated using an Alternative Binary Offset Carrier scheme. This method results in what is effectively two adjacent 20MHz wide signals centered on 1176 MHz and 1207 MHz (European Union 2010). Although this may be an oversimplification for many applications, it will suffice here.

Precise Timing

Precise time synchronization is critical to any pseudolite or MLAT type APNT solution. The relative synchronization of all the network nodes is directly related to the ranging and positioning precision of the system. The internal time reference that is used may be from any source, so long as each node follows the same reference. In the case of Locata and the UHARS, this time reference may be GPS time or the internal quartz oscillator of the master LocataLite (Locata Corporation 2011). Without a robust and precise method of synchronizing nodes, each node must be capable of maintaining accurate time on its own.

To maintain the required positioning accuracy of an APNT system, timing errors can be converted to range errors. Based on Required Navigation Performance (RNP) and surveillance accuracy requirements in NextGen airspace an APNT system will have to provide a positioning accuracy of 92.6m. Accounting for geometric DOP and estimated ranging accuracy of the APNT source, any time synchronization would have to be accurate to approximately 50 ns, or about 15 meters (Lo, Akos and Dennis, Time Source Options for Alternate Positioning, Navigation, and Timing (APNT) 2012). Achieving this level of accuracy over an area the size of the United States fortunately is not necessary. Nationwide reference to UTC within 20 seconds is sufficient to meet APNT and RNAV performance requirements (Reference chapter IV). Fortunately, nanosecond relative time synchronization is only necessary between those pseudolites in view of a single receiver and used for a position solution.

Synchronizing clocks can be broken into three components. First, the accuracy of the reference must be adequate. For flexibility and integration into other systems UTC may be used as a reference time standard. Space based references such as GPS and WAAS may achieve 15-30 ns accuracy. Second, a means of distributing precise updates to each node of the network must exit. Updates may be transmitted wirelessly from terrestrial sources, space based sources; or transmitted terrestrially via fiber or cable. Updates must be frequent enough to accommodate the drift rate of each node's internal clock. Third, an accurate frequency reference must be present at each node. The reference must be accurate enough to "drift" until the next synchronization update occurs or used as a hold over during interference and outages (Lo, Akos and Dennis, Time Source Options for Alternate Positioning, Navigation, and Timing (APNT) 2012).

Terrestrial, wireless distribution of an accurate time reference depends on the availability of line-of-site between pseudolites. Over flat terrain, each pseudolite in a UHARS type system would require a 400ft tall tower to synchronize clocks 50nmi apart due to the curvature of the Earth. This is not only impractical but the accuracy of the reference would degrade by 2 ns with each "hop" (Locata Corporation 2011). Terrestrial hard-wired connections would likely require a dedicated fiber to each pseudolite and may degrade by 5ns with each hop. Space based wide area synchronization is currently the only method practically available and capable of the precision required by APNT. Space based time synchronization is both practical and accurate but is vulnerable to interference and has common failure modes to the very navigation systems APNT is designed to backup.

As an alternative to the GPS, an APNT system must be able to tolerate reasonable interference and outages of the GPS. A precise frequency reference at each pseudolite, such as a Rubidium Oscillator, may be used to "coast" through a GPS outage for up to 12hrs at a cost of less than $1500 per clock (Lo, Akos and Dennis 2012). This would mitigate the effects powerful jammers or GPS outages unrelated to jamming. To provide robustness to jamming a pseudolite may use several techniques. In a 2010 paper to the FAA on timing sources, Lo, Akos, and Dennis describe controlled reception pattern antennas (CRPA) that may provide 20-40dB of suppression to terrestrial jammers. The GPS now transmits civil navigation signals on three frequencies, requiring jammers to spread their power over a broad spectrum. The higher power and architecture of newer GPS signals provides up to 15dB of resistance over older signals. Resistance to jamming provided by CRPA antennas, GPS modernization, and improved receiver design would likely prevent any wide denial of service to a space based time reference. An APNT network could be designed then, to accommodate localized outages of up to 12 hours with current technology.

Time Distribution

Locata's technique of time synchronization is one of its distinguishing characteristics from other forms of pseudolites. Through the process referred to as TimeLoc, each pseudolite adjusts the transmission time of its own signal to match the transmission time of a master pseudolite's ranging signal. The signals are matched in phase but with up to six cycles of ambiguity (Locata Corporation 2011). For a pseudolite to use TimeLoc, it must be able to receive the ranging signal of the master just as any user receiver would: via line-of-sight radio link.

The current architecture of Locata dictates that each pseudolite attempt to slave it's signal to a master. If the master is not in sight, the pseudolite will synchronize its clock to another pseudolite that is in view of the master. The pseudolites are then "daisy-chained" together and time distribution is cascaded beyond line-of-sight from the original master LocataLite. Distributing time via line-of-sight on a continental scale is almost certainly cost prohibitive because of the number of pseudolites that would be required. Accuracy of TimeLoc degrades with each step in the cascade as well. It should be noted here that this degradation is not cumulative, but only significant to the user in relative terms. Pseudolites on the east coast may be a full second off of pseudolites on the west coast if TimeLoc were cascaded across the country. The relative accuracy of each pseudolite in view of the receiver will determine position error due to clock error.

TimeLoc does provide a potentially valuable solution to robust time distribution. While cascaded TimeLoc on a continental scale is not likely, TimeLoc on a local scale could provide a backup to space based time distribution or help to improve the accuracy of a local network. Localized TimeLoc would rely on space based time distribution as a reference at the master LocataLite. The master would then distribute time via TimeLoc to all pseudolites in view. Cities such as Denver and Salt Lake City provide ideal geometry for this method. A master LocataLite placed high on the horizon could be in view of all pseudolites placed around the airport on lower, flat terrain. Each pseudolite could reference GPS time as an integrity check when available. LocataLite firmware could also be designed to autonomously restructure the LocataNet to designate any pseudolite with a strong GPS signal as the local master. This flexibility may protect against mobile GPS interference presented by personal privacy jammers.

III. Operational Architecture

To gain a fuller understanding of APNT and NextGen, a Systems Engineering approach was taken. Using the DoD Architecture Framework, Use Cases and a series of Operational Viewpoints (OVs) were first created. Part of the FAA's desired outcome for this research was to use Systems Engineering methods to determine if the UHARS could serve as a suitable APNT source. This portion of the architecture development takes a step back and will analyze the suitability of APNT performance requirements, as stated by the APNT team and within the APNT CONOPs, for meeting NextGen Operational Improvements. The architecture allows for a traceable connection from the Operational Improvements promised by NextGen at the enterprise level, to scenario based Use Cases and Operational Activities, finally to specific attributes and measures of any APNT system. Chapter IV will cover the System Views (SVs) in detail and specifically cover performance of the UHARS when applied to APNT

Use Cases and Operational Activities

The APNT CONOPS describes two unique scenarios that involve operations within NextGen airspace. The scenarios allow the reader to walk through every phase of flight, from pre-flight planning, to post-flight parking, and witness the interaction between the users and the NAS. The scenarios read like a narrative of each flight, with occasional interruptions to describe what would occur if GPS service (which NextGen operations will depend on for critical functions) were interrupted, expectedly or not. Between the two scenarios every phase of flight is covered and the associated functions of APNT are encountered. There are seven areas of emphasis in the scenarios that roughly fall into two categories. The first category involves collaborative (airlines, aircrew, and the ANSP) management of the airspace and information sharing. These areas are indirectly dependent on precision navigation and are not considered here. The second category involves 4D trajectory (4DT) management, aircraft separation, and increased flexibility of en-route and airport operations. An evolution of the routing in today's flight plans, 4DTs define the flight path in space and time that an aircraft is planned to follow. There are three areas of emphasis that were considered to build the Operational Activity Diagram in Figure 4:

- Trajectory Management – the process of defining and flying a 4DT that considers capacity, flow contingencies and many other performance-based factors, known as Trajectory Based Operations (TBO)
- Separation Management – the processes and procedures used to safely separate aircraft both on the airport surface and in the air
- Flexible Airports and Surface Operations – where procedures and tools are available to improve throughput, surface movement, and environmental performance. These areas of emphasis are directly enabled by precision area navigation.

The initial direction for architecture product development was to create a list of use cases from scenarios in the CONOPs. What soon emerged was a set of use cases in which the underlying activities were all common. A scheduled airline flight that wished to follow a 4DT ultimately must use the same methods and sources of navigation as a private flight. An air traffic controller will use the same tools to manage traffic approaching a busy airport as they would to provide flexible routing around a storm. After several iterations; a Use Case Diagram was developed to provide a graphic relationship of the Operational Activities related to positioning in NextGen airspace.

Figure 4 is a representation of the relationships between users, service providers, and the Activities derived from Operational Scenarios. The primary actors that will interact in NextGen operations are depicted on the left. The three primary actors are the Aircrew who operate the aircraft, Flight Operations who are responsible for flight planning and scheduling, and the ANSP who will work with both to ensure efficient, effective, and safe routing of aircraft. The actors on the right are service providers of enabling systems. In the center are the various activities directly related to position and timing. The top left corner of the diagrams lists aircraft "states" which will be discussed later in the chapter. Each activity in the diagram may occur during any phase of flight or aircraft state. The aircraft state, combined with the activity, will determine the performance required from APNT.

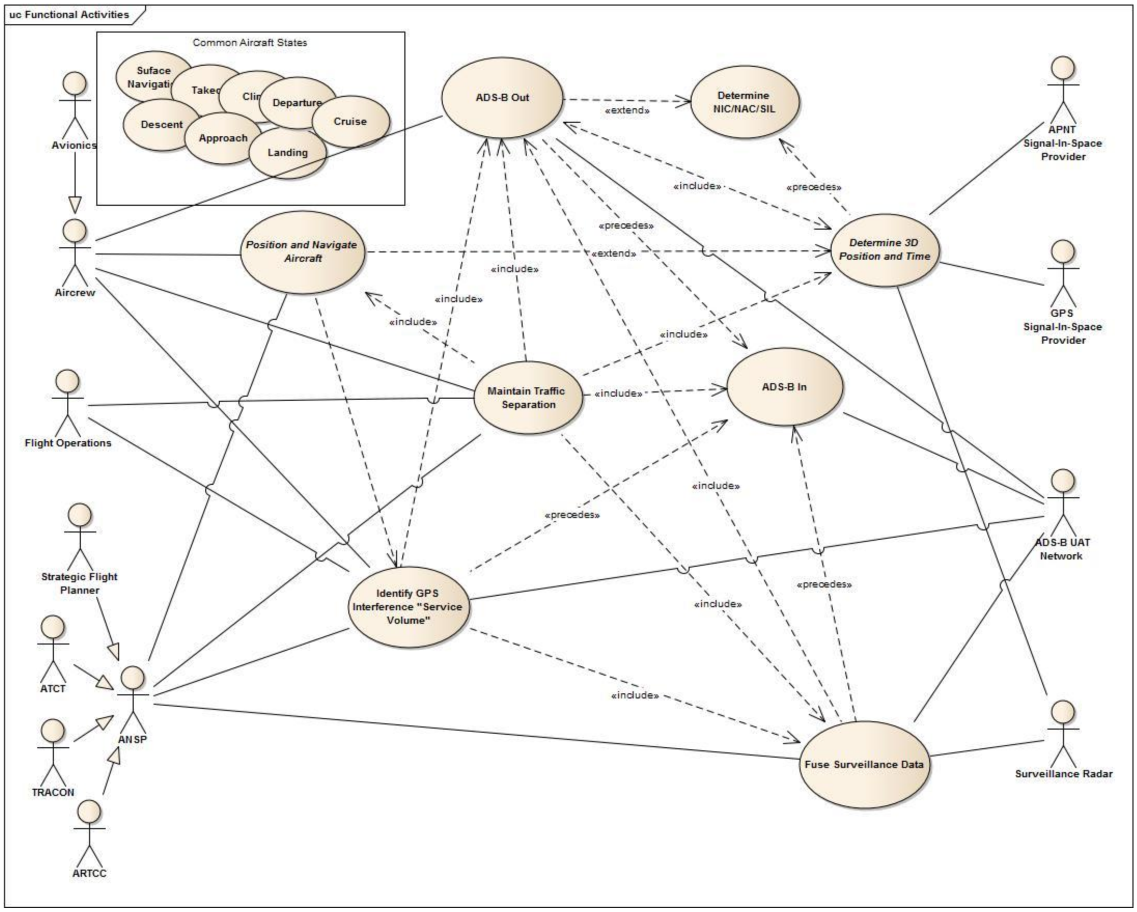

Figure 4: Operational Activity Model

What can be derived from this diagram is that all paths ultimately lead to determining an aircraft's position and time. Testing the system by introducing GPS interference, as is done in the CONOPs scenarios, reveals loss of service that significantly impacts smooth, safe operations of the NAS. As the FAA transitions to NextGen operations, surveillance RADAR coverage will be minimized for cost savings. Legacy navigation systems such as VOR and DME will also be gradually removed. While VOR, DME, and RADAR may exist in busy areas of the NAS, it will not be accurate enough for positioning and surveillance via ADS-B. Without an APNT source, in the absence of GPS, safe recovery of aircraft becomes questionable and increased capacity is lost in busy airspace. Without an APNT source suitable for ADS-B many of the benefits of NextGen would disappear.

The operational activities described above were traced to NAS services at the enterprise level. Each activity can be correlated to a service which the FAA is mandated to provide to the NAS. Figure 5 illustrates this correlation. Note that not all mission services are influenced by APNT. All supporting NextGen programs would be considered to gain a complete picture of NAS services.

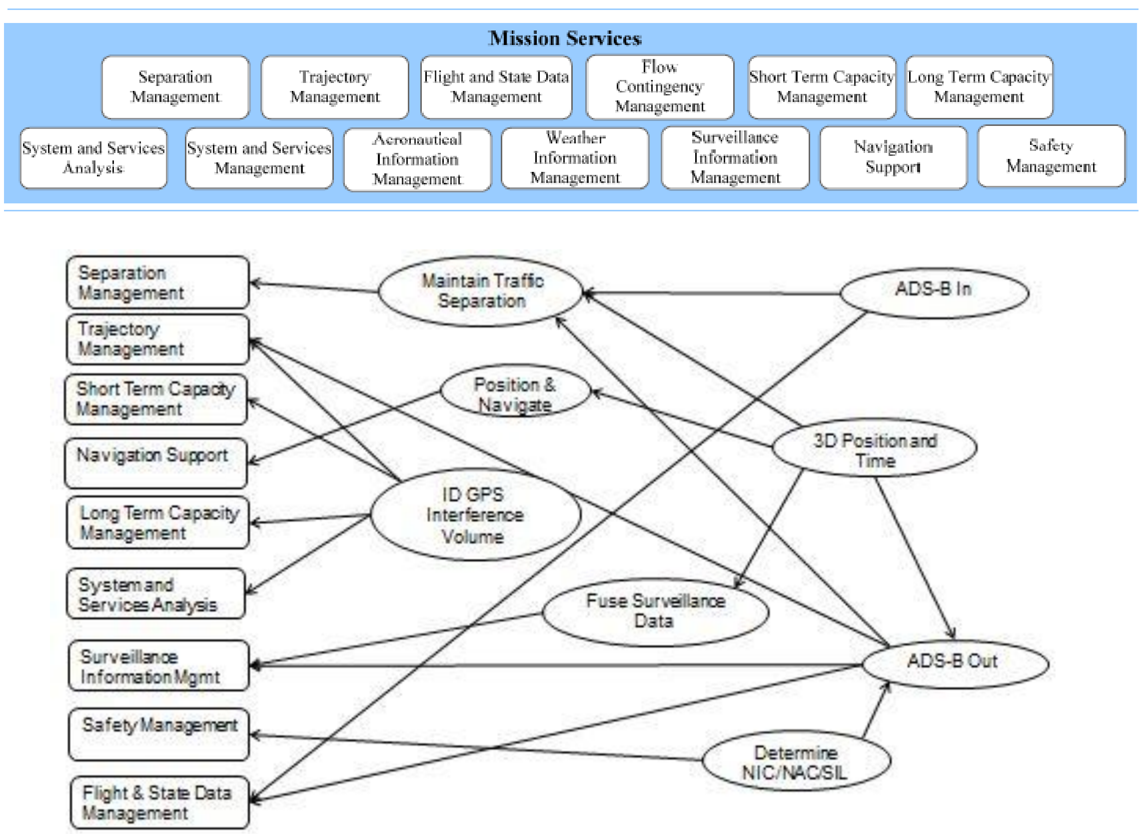

Figure 5: Enterprise Service Traceability

Activity Diagrams

The operational activities described above were developed in more detail using Enterprise Architect (EA). EA allows the user to build scenario based activity diagrams from structured use cases. This tool is simple to use as a starting point for developing activity diagrams. It offered an easy transition from the CONOPs scenarios to activity diagrams. The first step was to develop the activity (or use case) relationship model in Figure 4. The second step was to flesh out each use case with a basic path in the Scenario tool. Right clicking on any activity in the diagram, opening the "properties" tab, followed by the "scenarios" tab, will bring up the window depicted in Figure 6.

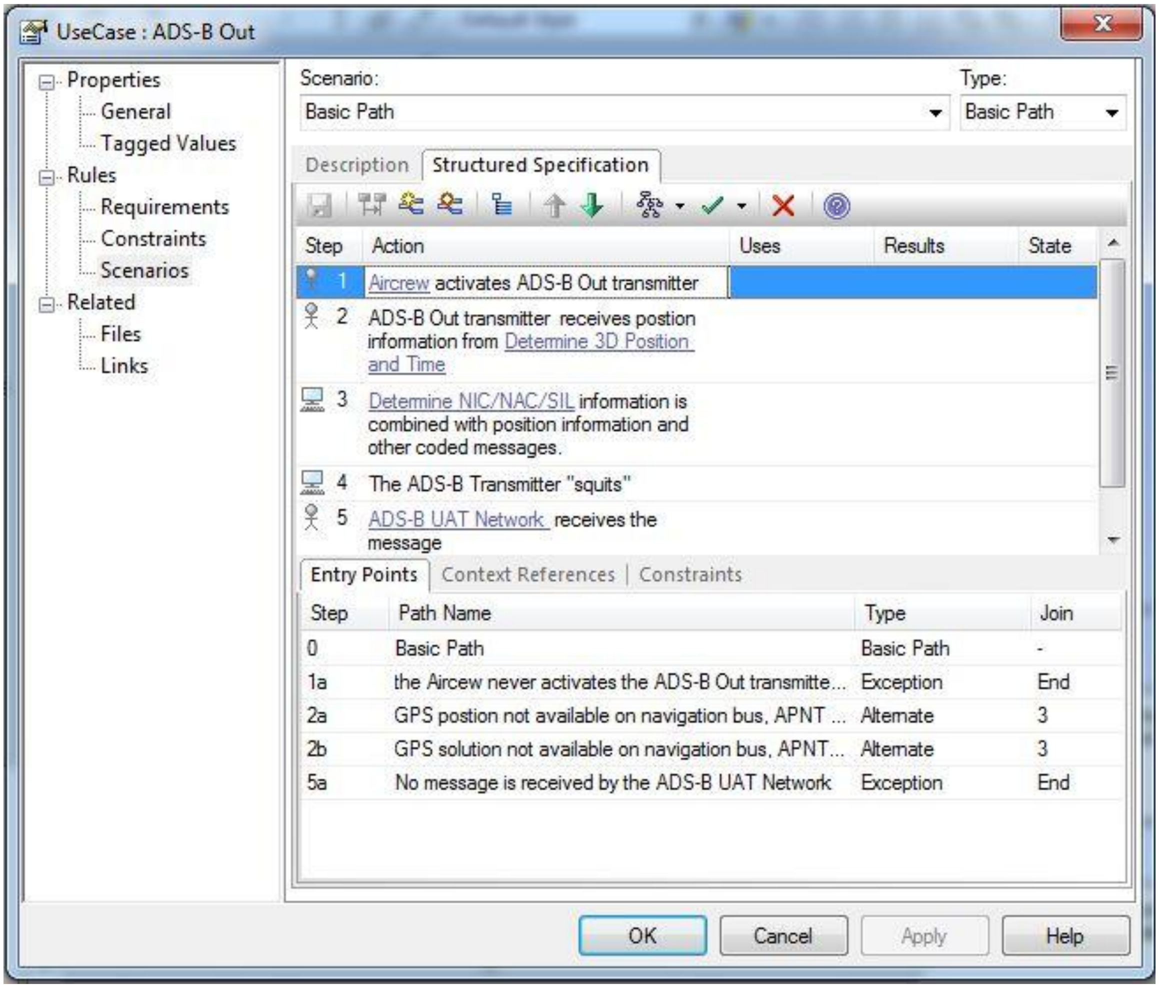

Figure 6: Scenario Based Activity Diagrams

From here basic paths are developed as the scenarios play out. Alternate paths can be developed at each step based on scenarios described in the CONOPS or other sources. Exception paths are entered when an alternate path to the desirable outcome does not exist. These may highlight system shortfalls that need to be addressed. Other activities referenced in Actions are automatically hyperlinked and a hierarchy of activities begins to form. Once all steps are entered EA will automatically generate an activity diagram that is consistent with the scenario. This diagram resembles the DoDAF OV-5 Activity

Model. The output is shown in Figure 7 for ADS-B Out. The output may not be optimized for viewing, or it may not include alternate paths, exceptions, or other details that should be included for completeness. The final draft of the ADS-B Out diagram is shown in Figure 8.

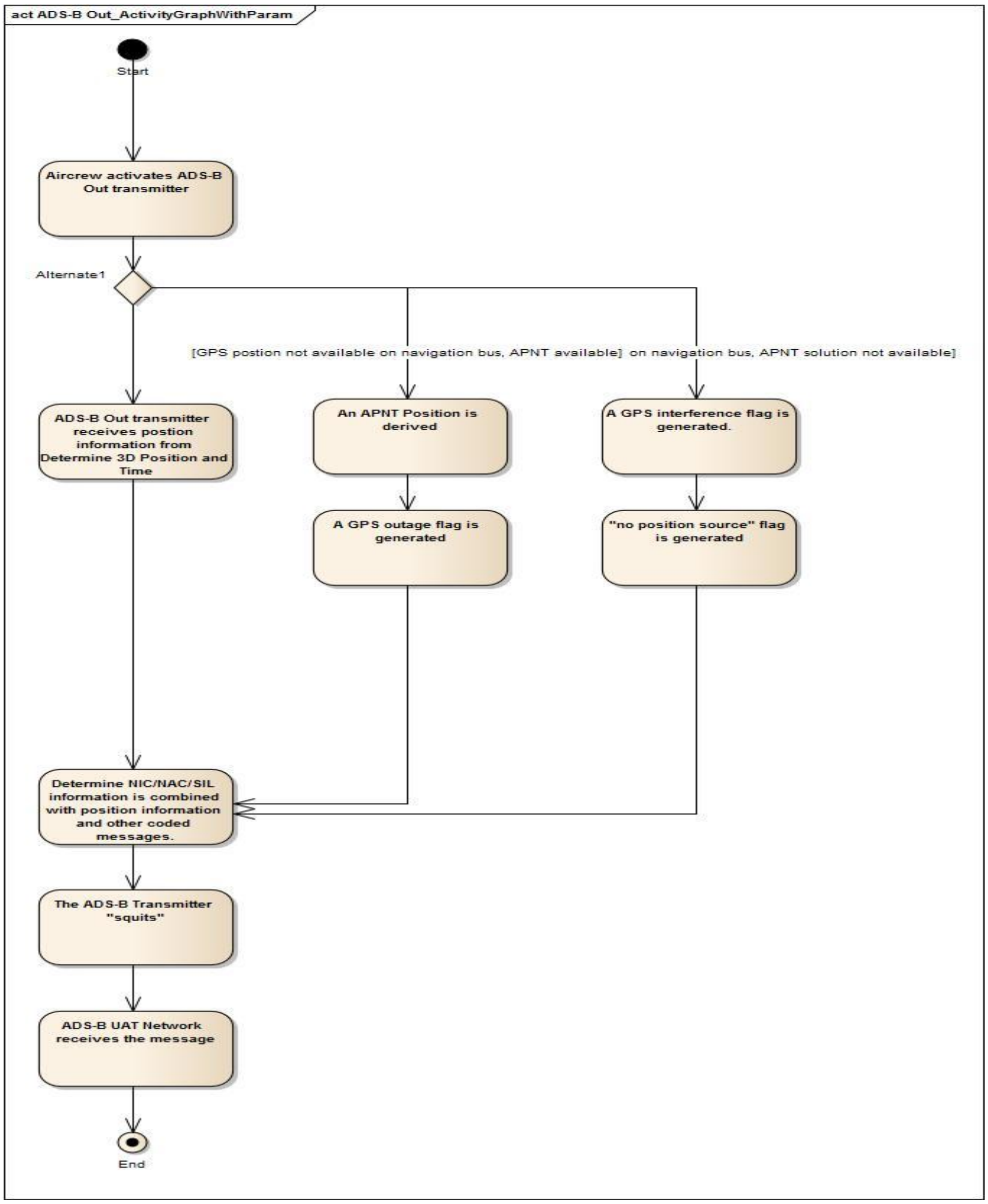

Figure 7: Auto-generated ADS-B Out

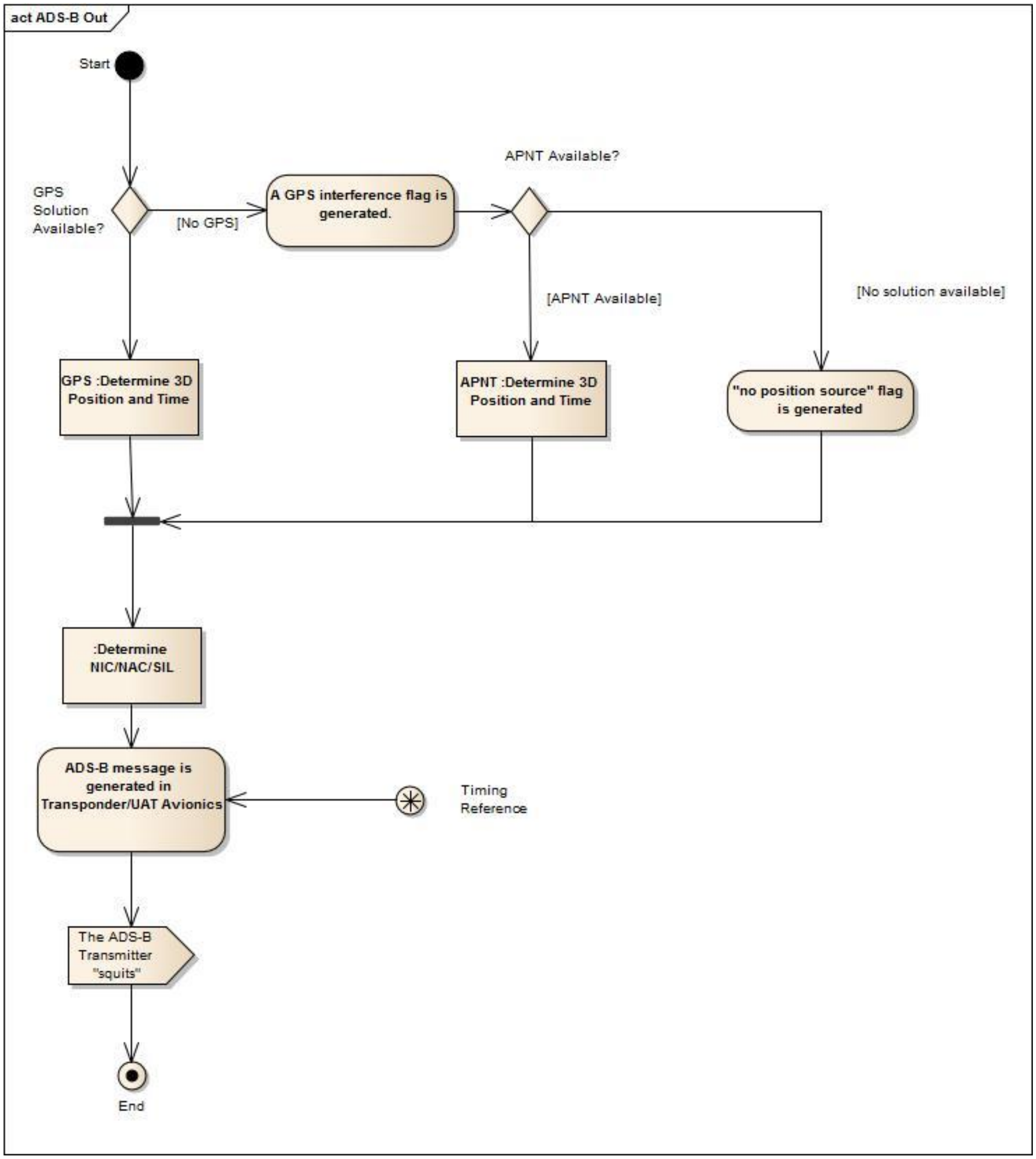

Figure 8: Final ADS-B Out

This is a powerful tool for developing activity diagrams that are consistent with scenarios and use cases. It also provides a convenient way to show the interaction between activities. It is important to remember that the initial auto-generated diagram is only a time saving step and should be thoroughly reviewed to make sure it is clear and complete. Iteration between the activity diagram and underlying use case scenarios should be expected.

Each complete activity diagram can be used to highlight the alternate paths that exist and those which must be utilized in the absence of GPS. The activities modeled are those which relate directly to determining 3D position and time and are predicated on the aircraft involved being in controlled airspace and utilizing ANSP services. Aircraft operating under visual flight rules (VFR) can always continue to a safe landing without the aid of APNT, although benefits of improved SA are lost. Airline flights must file IFR and would be significantly impacted even in good weather. The alternate paths shown generally result in an exception path when no acceptable outcome exits. If a safe, but perhaps less desirable outcome exits, the alternate path is shown. Detailed discussion of some unacceptable outcomes and alternate paths is embedded in the EA file and should be continuously updated as the FAA matures its plan for APNT. Below is a brief discussion of the activity diagrams and what they reveal.

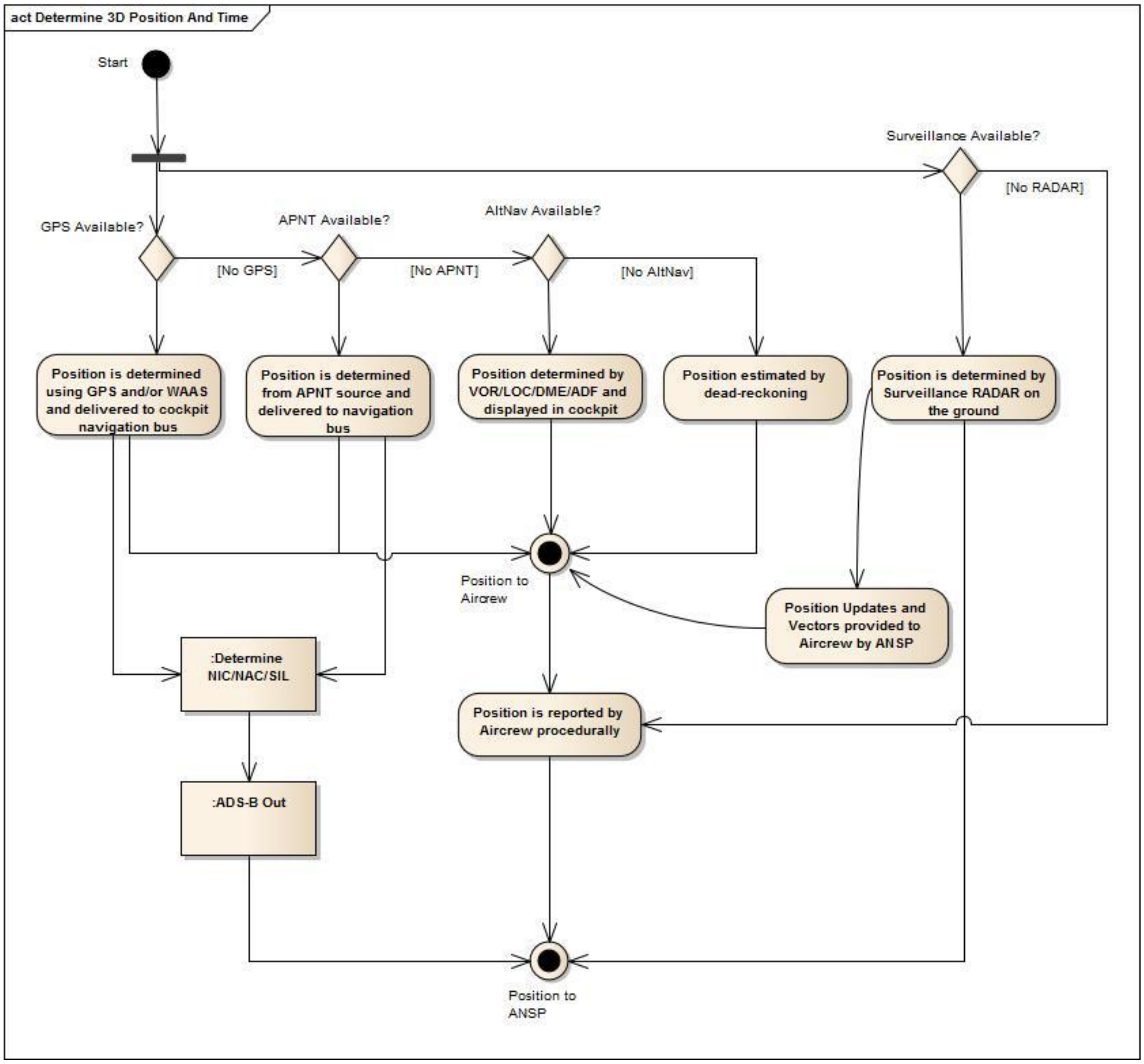

Figure 9: Determine 3D Position and Time

The multiple paths for determining an aircraft position are depicted in Figure 9 above. Five positioning sources are listed; GPS and APNT being the most precise and preferred methods in NextGen 2025. The accuracy, integrity, and availability of the position source will vary depending on the path chosen along with several other factors and is not shown in this diagram. Two important takeaways from this diagram are as follows. First, only GPS or an APNT source compliant with 14 CFR Part 91-314 (the

Federal ruling on ADS-B operation and performance) will be acceptable for ADS-B Out. The CFR ruling on ADS-B requires a horizontal position accuracy of 92.6m during all phases of flight. The second point of note is that as legacy navigation aids are removed and surveillance RADAR coverage is reduced, no acceptable means of determining position would exist in the absence of GPS or APNT.

Figures 10 and 11 below illustrate Navigation and Surveillance; activities which were once carried out by aircrew and the ANSP exclusively. In NextGen 2025 the lines are blurred when surveillance becomes dependent on aircrew (via ADS-B Out) reported position. In the event of GPS interference or outage both surveillance and navigation performance levels are reduced or lost entirely.

The conclusions drawn from all of these architecture products begin to appear the same after only a few iterations. Without stating anything about required performance levels (other than GPS is currently the only source that meets all accuracy requirements) it is apparent that an APNT source is necessary for navigation and dependent surveillance.

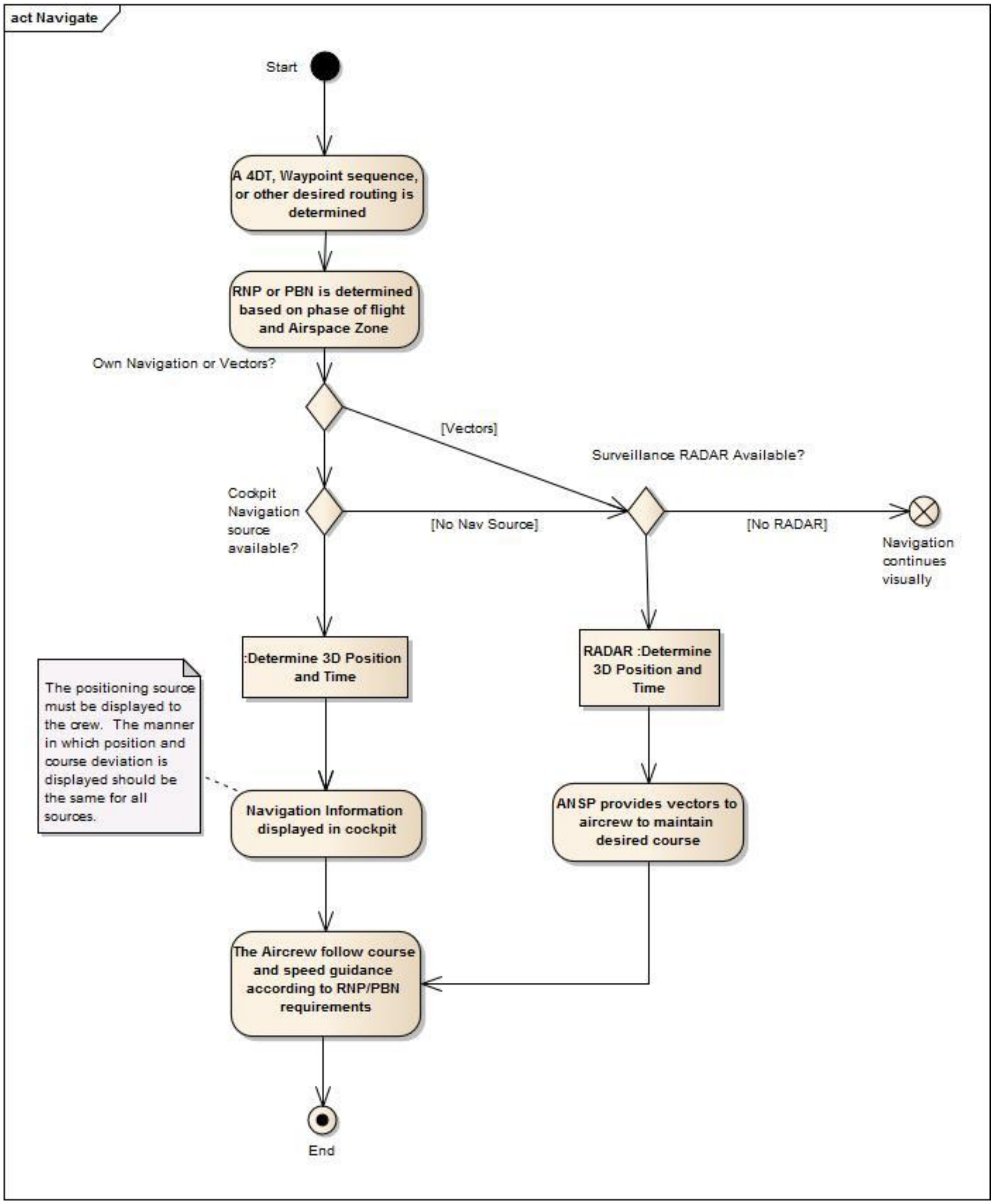

Figure 10: Navigate

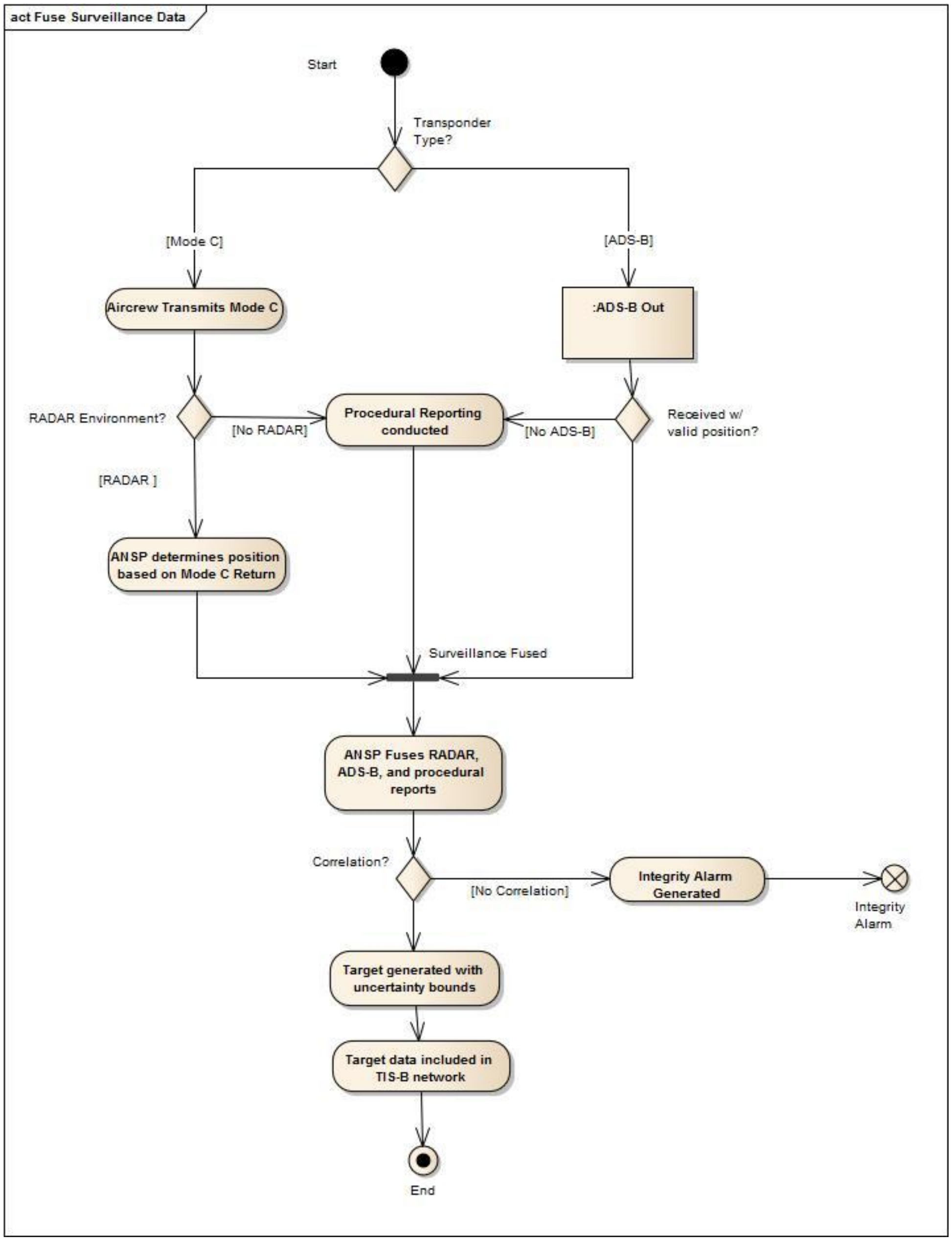

Figure 11: Fuse Surveillance Data

Operational Nodes

An Operational Node Diagram, or OV-2, was created in conjunction with the Activity diagrams above. Figure 12 illustrates both the “To-Be” and “As-Is” connectivity of operational nodes relative to APNT. The functions performed at each node are listed. The connections shown in red are those that must be provided with an APNT source.

Two critical connections are drawn from the APNT source to the Aircraft and to the UAT network. These connection paths will include the Position reference provided by APNT as well as the time reference required for operations in the NAS. Providing position is the primary role of APNT but precision time can be equally as critical. Currently, time reference to UTC +/- 30 seconds is all that is required (Federal Aviation Administration 2012) for TBO and operations within the NAS. The red, bolded connectors with a "?" attached indicate the potential need for a more precise timing reference source. APNT (in pseudolite form) will require much more precise timing synchronization (on the order of Nano seconds) than the operational requirements of the NAS. This may come from the GPS or other GNSS source, or it may come from an as yet undefined terrestrial source. ANSP and UAT functions that rely on TDMA communications could also benefit from the presence of an Alternate Precision Timing reference to the GPS. The APNT CONOPs has scoped the FAA's work to *exclude* this precision timing capability except as required for pseudolite clock synchronization.

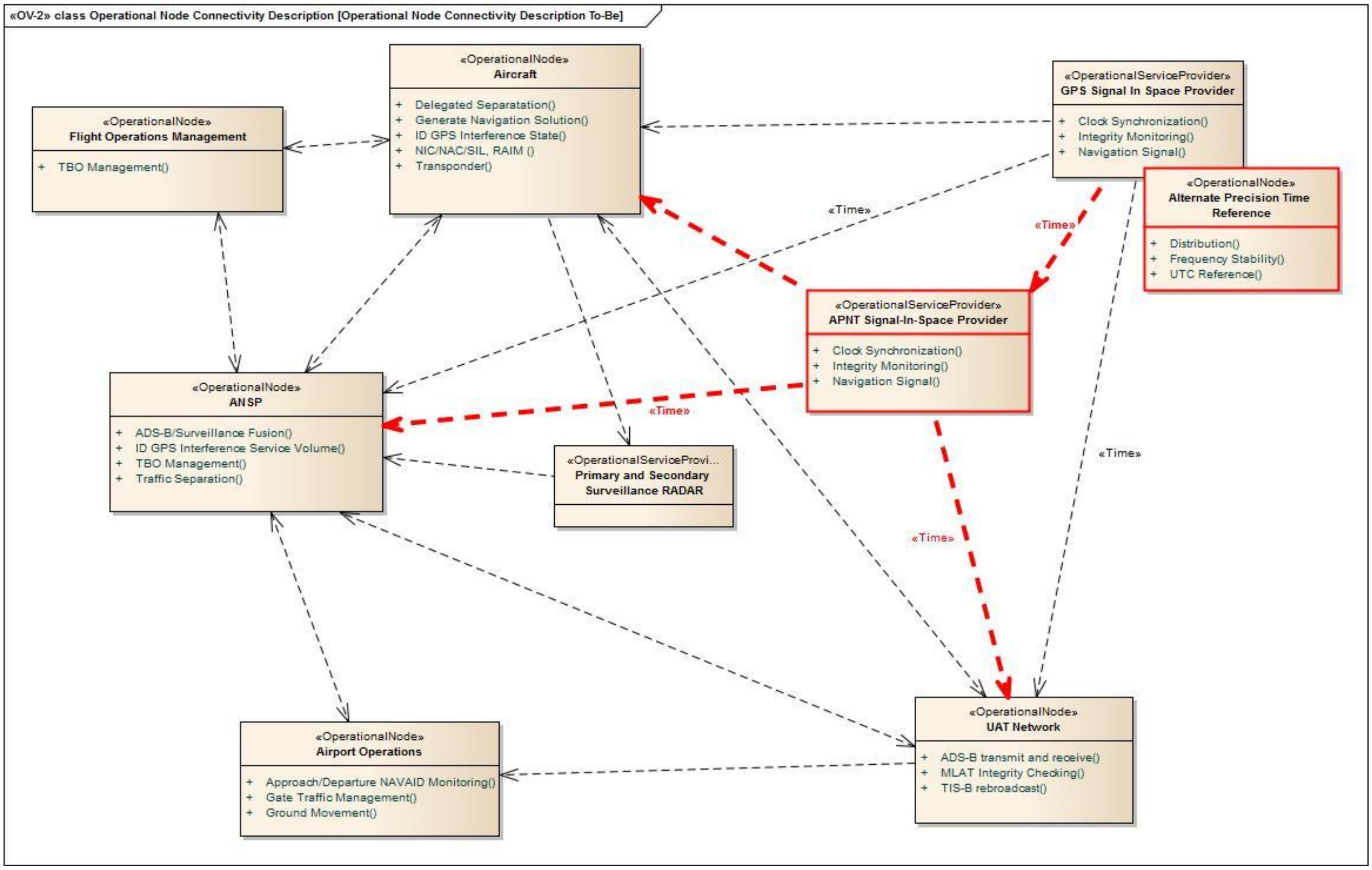

Figure 12: Operational Node Connectivity

Performance By Zone

The activity diagrams described above indicate the need for position and timing reference but they do not provide insight into what level of performance is required. Several questions must be asked about the APNT source. How accurate must my position be? What is the probability accuracy might exceed these limits without my being aware of it? Where, and when must it be available? The activity diagrams are inappropriate for answering these questions because they would have to be modified for phase of flight, airspace designation, or other potentially limitless scenarios. To begin to answer these performance questions, aircraft "states" and APNT "Zones" were pulled from the APNT CONOPs and correlated.

APNT Zones are defined in Figure 13 below. The precise definition of Zone 3 may change to accommodate a larger percentage of arrivals. The number of airports currently being considered for a Zone 3 Terminal area is 135 and is based on the amount of traffic that each airport handles in a given year. Zone 1 and 2 cover all of CONUS and are distinguished only by altitude. There are spaces in this diagram that are not to be serviced by APNT. Everywhere below Zone 2 and Zone 3 cones will be without APNT service. Ground traffic will not be serviced by APNT. This will have an impact on departures and arrivals at airports without a Zone 3 service volume overhead, requiring aircraft to climb to 5000' AGL before reaching navigation service.

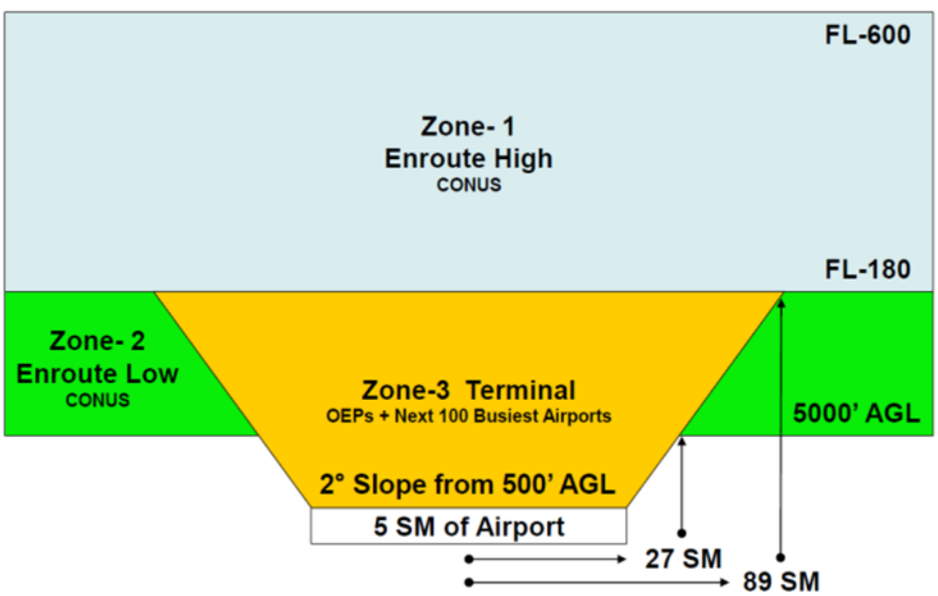

Figure 13: APNT Zones

Table 1 describes each aircraft state in the APNT CONOPs. It is a complete list of possible states from the beginning of a flight to the end of a flight. These aircraft states, combined with APNT Zone can be used to define the level of performance required from APNT. In the APNT CONOPS scenarios an aircraft utilizes GPS in every state and is affected in some way by loss of GPS. Refer to the GPS CONOPs for a detailed description of these effects.

Table 1: Aircraft States

Aircraft State Number	Aircraft State Name	Description
01	Parked	The aircraft is parked at the gate or on the ramp and the starting/ending point for flight
02	Taxi-Out	The aircraft has started taxiing to the assigned runway for takeoff
03	Takeoff Position	The aircraft is in position on the runway and ready to start the takeoff roll
04	Takeoff Roll	The aircraft is advancing down the runway and lifts off
05	Initial Climb	This is the segment where gear are retracted, power is reduced for climb and the aircraft begins to follow the flight path for departure
06	Climb	The aircraft is climbing along a prescribed path following a departure procedure and there may be level-offs during the climb for other traffic
07	Cruise	This is the en route phase of flight
08	Top of Descent	A point in space and time where the aircraft will start a descent toward the destination
09	Initial Descent	The segment of the descent that begins at the end of cruise and continues until the aircraft has begun an arrival to an airport
10	Arrival	The segment flown on a path leading to the start of an approach procedure; in the Current Environment a standard terminal arrival route
11	Initial Approach	Approaching on an intercept to a final approach path segment in the Current Environment and any segment that leads to a turn to final approach in the target environment
12	Approach	The segment between the final approach fix and decision height
13	Missed Approach	The path flown that begins at a point inside the final approach fix and continues to the missed approach waypoint.
14	Landing	From decision height to touchdown
15	Landing Rollout	The segment on the runway where the aircraft is decelerating and exiting the runway
16	Taxi-in	The segment where the aircraft is proceeding to the gate or ramp
17	Leader Aircraft	The aircraft is leading along a trajectory where another aircraft is following and maintaining spacing off of the leader
18	Follower Aircraft	The follower is using ADS-B-In information to station keep on the leader

Based on discussions with the FAA's APNT team and the APNT CONOPs, APNT designs must only support aircraft states 6 through 11. There is no requirement for APNT on the ground. Ground surveillance from MLAT exists at larger airports. For now, secondary airport ground operations may suffer during low visibility in the absence of GPS. APNT is not required beyond the Final Approach Fix (FAF) or in terminal areas not covered by Zone 3. ILS will be used to guide aircraft to the runway below approximately 1500' AGL. Departures may be delayed or cancelled at smaller airports, or for aircraft not equipped with more expensive RNAV equipment. Figure 14, below, illustrated which aircraft states are likely to occur in each APNT Zone. This figure is perhaps the most revealing of the architectural products. The vertical "swim lanes" indicate the associated Zone. The bubbles indicate the aircraft activity or state. Notice that several activities are duplicated. For example, aircraft will be arriving and departing from both secondary airports and those serviced by Zone 3 APNT so two instances of Arrival are depicted. Boxes around activities indicate navigation and surveillance services provided. Secondary RADAR coverage and VOR minimum operating network (VOR MON) coverage will be significantly reduced in NextGen 2025, increasing reliance on the GPS and APNT.

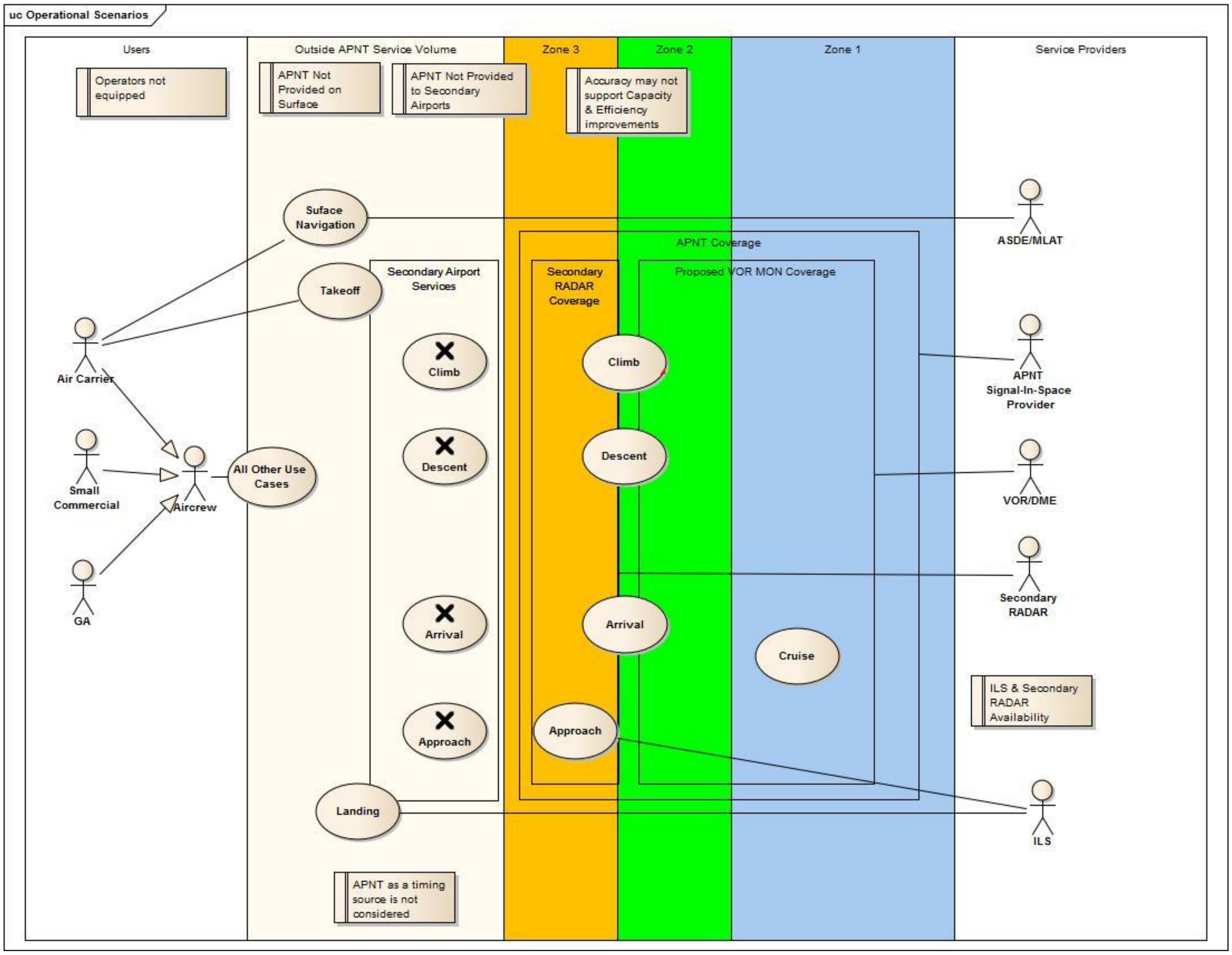

Figure 14: Operational State by APNT Zone

The attributes, measures, and performance requirements which are used to describe an APNT service are common to precision navigation and surveillance sources in use today. Several references are used to build a complete picture of these values including U.S. Code of Federal Regulations and the International Civil Aviation Organization (ICAO) Standards and Recommended Practices. A compilation of these values can be seen in Appendix A which is taken from the APNT CONOPs. Columns correlating APNT Zone and Aircraft state to performance have been added.

Appendix A divides criteria into categories of navigation, surveillance, and timing. Each category has unique attributes and measures associated. Table 2, below, outlines the attributes and measures that will be applied to APNT. The final two, capacity and compatibility have been added in this report for completeness. Pseudolites, by design and similar to the GPS, have no capacity limit. Compatibility is considered in Chapter V and has many facets. An APNT system must not interfere with other critical NAS systems and it must be integrated into every aircraft that will operate in controlled airspace.

Table 2: Attributes and Measures

Attributes	Measures
Accuracy	Navigation Accuracy Code (NAC) - 95% probability that reported position is within a specified distance of true position
Integrity	Navigation Integrity Code (NIC) -10^{-7} probability of exceeding this boundary per flight hour or per approach
Surveillance	Surveillance Integrity Limit (SIL) - Probability of exceeding NIC per flight hour or per approach without alarm
Availability	Probability of availability per flight hour for any given operation
Continuity	Probability of continuous avalailability for a prescribed time period, given availability at the beginning of an operation
Capacity	Total number of users simultaneously supported for all operations in a given service volume
Compatibiliy	Simultaneous operation with other cockpit avionics and wireless systems in the NAS.

Finally, the minimum performance requirements for each APNT Zone can be derived. Traceability from Activity to State to Zone in the preceding sections has been established. The table in Appendix A can be reduced to the most demanding requirements in each Zone. The following steps were taken to reduce Appendix A to Table 3.

- Eliminate all flight operations (rows) that do not occur in an APNT Zone
- Compare Accuracy and NAC, keep the lower of the two values. Surveillance is always more demanding.
- Compare Containment and SIL, keep the lower of the two values. Again, Surveillance is more demanding for all cases.
- By Aircraft Zone, determine the most demanding performance values in the remaining cells.

Table 3: Desired Performance Levels

	Navigation		**Surveillance**				**Continuity**	**Time Performance**
	Nautical Miles		Nautical Miles					+/- Minutes
	(≥99.0% Availability)		(≥99.9% Availability)					RTP[1]
	Accuracy	Containment	Separation	(NACp)	(NIC)	(SIL)		
Airspace Zone	(95%)	(10^{-7})					/flight hour	
S	N/A							
1	1	2	3-5	0.05 (8)	0.2 (7)	10^{-7} (3)	10^{-4}	1
2	1	2	3	0.05 (8)	0.2 (7)	10^{-7} (3)	10^{-4}	2
3	0.3	0.6	3	0.05 (8)	0.2 (7)	10^{-7} (3)	10^{-5}	20 sec

Table 3 provides the performance requirements that will be evaluated in Chapter V. Navigation and surveillance are kept separate to illustrate the more demanding requirement that Surveillance will place on an APNT system. While surveillance RADAR systems are still in operation around our nation's busiest airports the performance requirements of APNT might be relaxed to those of navigation. This table answers the simplest question, “How accurate does APNT have to be?” Any APNT source has a desired 95% accuracy of .05 nautical miles (or 92.6 meters) and an integrity limit of .2 nautical miles. This would be sufficient to support 3 mile separation of aircraft in all Zones.

Table 4 illustrates the minimum performance levels of APNT set by the FAAs APNT team. The APNT team has stated that required performance could be relaxed to 185 meters for accuracy and 1 nautical mile for integrity. This is sufficient to support 5 nautical mile separation and may support safe recovery of aircraft in less congested airspace. It is worth noting here again that CFR Part 91-314, the amendment governing ADS-B, mandates 92.6m accuracy for surveillance purposes.

Table 4: Required Performance Levels

	Navigation Nautical Miles (≥99.0% Availability)		**Surveillance** Nautical Miles (≥99.9% Availability)			**Time Performance** +/- Minutes RTP[1]
Airspace Zone	Accuracy (95%)	Containment (10^{-7})	Separation	NACp (95%)	NIC (10^{-7})	
S	N/A					
1	2	4	5	0.1 (7)	1 (5)	1
2	2	4	5	0.1 (7)	1 (5)	2
3	1	2	5	0.1 (7)	1 (5)	20 sec

Operational Improvements

The objective of this section is to determine if the stated performance level and implementation of APNT described above will enable the planned Operational Improvements of NextGen. NextGen planning is a collaborative effort between several departments of the executive branch, including the Department of Transportation and the FAA. The collective effort is referred to as the Joint Planning and Development Office (JPDO). The JPDO has developed a set of operational improvements to support the NextGen operational activities of 2025. The comprehensive list contains 136 OIs that affect flight planning, data sharing and management, navigation, safety, environmental protection, and other areas. (JPDO 2012) The FAA has approved a set of 94 OIs (FAA 2012) that are conveniently categorized by the enterprise level services and solution sets they associate with. For this analysis the list was reduced to 65 that are related to navigation or are affected by precision navigation and timing.

The first step was to combine and consolidate the FAA and JPDO OIs into a single list. The reference numbers of each OI are retained to show where there is overlap and which OIs were unique to one organization. The FAA CONOPs has listed the potential impact of GPS interference on each OI in the absence of an APNT source and described how APNT might mitigate the impacts. This was carried through to the remaining JPDO OIs. The level of impact is described on a scale of 1 to 3; a 1 meaning the OI would not be possible without APNT or GPS, 2 meaning the OI would only partially be realized, and 3 meaning the OI would be unaffected by GPS outage regardless of APNT.

The second step was to associate performance zones and aircraft states to each OI. If an OI applies to more than one zone or state they are listed as well. In many cases the OI applies to ground operations or secondary airports that would not be covered by Zone 3. These are annotated with an “S”, “All”, or the shortfall description includes lack of coverage for secondary airports.

The third step was to evaluate each OI based on the associated performance zone and aircraft state, and the details of the OI as they relate to pseudolite based APNT. The level of APNT support can then be determined on the same 3 point scale described above. If the OI is not supported by APNT the OI receives a 1. If the OI is fully supported it receives a 3. If APNT is not planned to support the zone associated with an OI it receives a 1. This is an objective association. OIs that relate to supporting general aviation or increasing capacity and flexibility at secondary airports are harder to evaluate and the shortfall rating becomes more subjective.

Of the 63 OIs evaluated 22 were rated with a 1 or a 2. The majority of these shortfalls are because of a lack of APNT provided on the surface. The second most common shortfall is due to incomplete coverage of the NAS. APNT Zone 2 will only serve 5000’ AGL and above and Zone 3 is only planned at 135 airports. Secondary airports will not be supported by APNT and many OIs relate to increasing access and flexibility at secondary airports. A third common shortfall is due to lack of precision or service during the approach phase of flight. Many OIs that promise to increase capacity in busy airspace or continued seamless operation during GPS outage rely on precision approaches and RNAV flexibility. If APNT is limited to supporting only navigation to an ILS approach these OIs may only partially be supported. Figure 15 below is a section of the complete OI shortfall analysis posted here for convenience.

FAA Identifier	JPDO Identifier	Targeted NextGen Capability For 2025	APNT Function	Impact	APNT Supported?	APNT Gap	Key Attributes	Aircraft States	Performance Zone	Name	Description	Benefits	Solution Set	Service
105208	303		Provides information to the ANSP when APNT is in use to identify GPS system area outages	1	3		Availability, Compatibility, Capacity	All	All	Traffic Management Initiatives with Flight Specific Trajectories	Individual flight-specific trajectory changes resulting from Traffic Management Initiatives (TMIs) will be disseminated to the appropriate Air Navigation Service Provider (ANSP) automation for tactical approval and execution. This capability will increase the agility of the NAS to adjust and	* Improved efficiency * Increased capacity * Improved predictability * Reduced fuel-burn and aircraft emissions	Improve Collaborative ATM	TM-Strategic Flow
101103	306	x	Provides position to airborne and ground automation to continue the capability to exchange flight planning information and negotiate flight trajectory agreement	2	2	Not provided on surface	Availability, Continuity	All	All	Provide Interactive Flight Planning from Anywhere	Flight planning activities are accomplished from the flight deck as readily as any location. Airborne and ground automation provide the capability to exchange flight planning information and negotiate flight trajectory agreement amendments in near real-time. The key change is that	Increased efficiency Increased accessibility Enhanced user-preferred trajectories	Initiate Trajectory Based Operations	Flight Planning
104122	307		Provides position to continue RNP and RNAV operations while maintaining 3nm separation standards	2	3		Accuracy, Compatibility	6, 8-13	1, 3	Integrated Arrival/Departure Airspace Management	New airspace design takes advantage of expanded use of terminal procedures and separation standards. This is particularly applicable in major metropolitan areas supporting multiple high-volume airports. This increases aircraft flow and introduces additional routes and flexibility to reduce delays.	* Maximizes throughput * Improved efficiency * Reduced flight time * Reduced noise * Reduced fuel burn and engine emissions	Increase Arrivals/Departures at High Density Airports	TM-Synchronization
104124	309		Enables aircraft to remain on original flight plan to include the most economical point in which to begin a descent using the most economical power	1	3		Accuracy	8-11	3	Use Optimized Profile Descent	Optimized Profile Descents (OPDs) permit aircraft to remain at higher altitudes on arrival to the airport and use lower power settings during descent. OPD arrival procedures will decrease noise and be more fuel-efficient. The air navigation service provider procedures and automation	*Reduced noise *Reduced fuel-burn and engine emissions	Increase Flexibility in the Terminal Environment	TM-Synchronization
	310		Provides position to GA aircraft for ADS-B positioning for more direct routing through busy terminal area airspace	1	2	Cost prohibits acces to GA	Accuracy, Availability, Integrity, Compatibility, Capacity	6-11	3	Improved GA Access to Traverse Terminal Areas	This Operational Improvement (OI) results in increased access to busy airspace, such as Class B, for General Aviation (GA) operators. More direct routing for GA operators is facilitated through improved access to traverse busy terminal area airspace via the continued use and possible expansion	Increased efficiency Increased accessibility Enhanced user-preferred trajectories	Increase Flexibility in the Terminal Environment	ATC-Separation Assurance

Figure 15: OI Shortfall Traceability Matrix

This iteration of pairing OIs to performance is an incomplete example of how APNT will support NextGen 2025 but it does illustrate the discontinuity between stated objectives and planned performance. This method of relating APNT performance to Operational Improvements should be iterated with each decision milestone of APNT planning as details are fleshed out. APNT does appear to support the four pillars described in the CONOPS but one should ask: "What system will fill the APNT gaps highlighted?

The APNT team has highlighted the following four "pillars" of APNT.

- Safe recovery (landing) of aircraft flying in Instrument Meteorological Conditions (IMC) under Instrument Flight Rule (IFR) operations
- Strategic modification of flight trajectories to avoid areas of interference and manage demand within the interference area
- Continued dispatch of air carrier operations to deny an economic target for an intentional jammer
- Flight operations continue without a significant increase in workload for either the pilot or the Air Navigation Service Provider (ANSP) during an interference event.

APNT will provide means for a safe recovery of aircraft but may not allow aircraft to arrive at their intended destination. APNT will allow modification of trajectories but is constrained by APNT Zone coverage. APNT will allow continued dispatch of aircraft, but at potentially reduced capacity due to less precise positioning until at altitude or non-universal equipage. Continued operation without an increase in workload will require that flight planning be based on the least capable navigation system available for a given operation. For example, if GPS allows less than 3 mile separation in busy airspace and aircraft are allowed to reduce separation, in the event of a GPS outage, controllers will have to manage re-spacing aircraft as navigation reverts to APNT.

Relying on ILS for approach could also significantly increase workloads as aircraft are re-routed to available approaches.

IV. UHARS System Architecture & Signal Performance Analysis

Chapter Overview

Chapter IV takes a closer look at Locata and the UHARS as they could be applied to the APNT problem. The first section is a collection of Systems Views (SVs) that describe the architecture of a Locata network. They illustrate the system nodes, connections, and related functionality of a Locata Net. In principle, these SVs could describe an APNT system on a continental scale but in reality it is precisely this scale that will raise issues.

The second section describes the signal structure of Locata and proposes potential changes to certain properties. Most changes to the Locata signal reflect the need to integrate with existing radio systems in the ARNS band while propagating an APNT signal for over 100nmi from hundreds of sites around the country. With the proper signal masking it may be possible to increase the range of a Locata pseudolite with few other changes to the signal and those options are presented here as well.

The final sections describe the predicted performance levels of a potential signal structure and pseudolite network. The primary measure of positioning performance here is user range error (URE). Factors such as DOP from poor signal geometry, or unpredictable tropospheric errors may have a large effect on positioning accuracy and are only roughly modeled. Based on the estimated service volume and accuracy of each pseudolite, a rough estimate of the number of pseudolites required to cover Zones 1, 2, and 3 can be obtained. This analysis has been completed for other APNT solutions and is referenced here.

System Architecture

Locata networks have two primary segments. The first is the terrestrial segment of pseudolites. This can be compared to the space segment of the GPS or other GNSS. Each pseudolite broadcasts a ranging signal with an over-laid data stream that includes (but is not limited to) surveyed location on the surface of the earth. GPS satellites broadcast orbital parameters that can be used to compute their position as a function of time. The second segment is the user segment, which is the same as the GPS user segment. User equipment compares ranging signals from multiple pseudolites (in the same manner as GPS satellites) which are presumably transmitted simultaneously or with known error. These ranging signals can be used to determine user position and clock error relative to the pseudolites' frame of reference. Locata nets and the UHARS do not have a control segment like the GPS. Once Locata nets are surveyed and initialized they become autonomous although not entirely independent. Exceptions include time synchronization and meteorological data collection. Locata pseudolites require an external time reference to maintain synchronization to UTC. Within the Locata network time is maintained by referencing the phase of signals sent between pseudolites via line of site radios. This is referred to as TimeLoc. The UHARS utilizes this method of time synchronization. To correct for tropospheric signal delay pseudolites broadcast meteorological data including temperature, pressure, and relative humidity. Collecting this information requires additional hardware.

Locata network and signal architecture resembles the GPS in many ways. There are a few key differences so solve problems that arise when operating a terrestrial pseudolite system. TimeLoc is perhaps the most unique aspect of Locata technology. GNSS require multiple precise clocks on board each satellite and extensive control segments to keep each satellite clock synchronized. Locata gets around this challenge by linking each pseudolite to a master pseudolite and synchronizing their navigation signals to phase level accuracy. Each slave LocataLite receives the navigation signal broadcast by the master LocateLite. Based on surveyed distance between the LocataLites and signal error correction models, the slave LocataLite can determine the cycle ambiguity of the pseudo-ranging signal to approximately 6 cycles (Locata Corporation 2011). In this manner, with no outside time or frequency reference, the inexpensive quartz oscillator in the master LocataLite is sufficient for nano-second time synchronization and centimeter level accuracy. The trade-off is that TimeLoc requires a line of sight wireless link between each pseudolite.

The second unique quality of Locata technology, relative to GNSS, is its adaptation to solve the near-far problem of received signal strength. GNSS benefit from nearly uniform separation between any user's receiver and the satellite constellation. The 23dB of separation provided by the 1023 chip Pseudo Random Noise (PRN) code is more than adequate to separate multiple signals. User range to a LocataLite in a UHARS scale application may vary from hundreds of meters to a hundred kilometers. Receiver dynamic range could not accommodate simultaneous reception of both near and far signals. Locata incorporates a TDMA scheme to further separate the signals of each Locate Lite. Figure 16 illustrates this and will be described in detail later in the chapter. What should be noted here is that each TDMA frame offers 10 time slots to broadcast a navigation signal. In this manner, up to 10 LocataLites could theoretically broadcast using the same PRN code in the same geographic area and not interfere with each other.

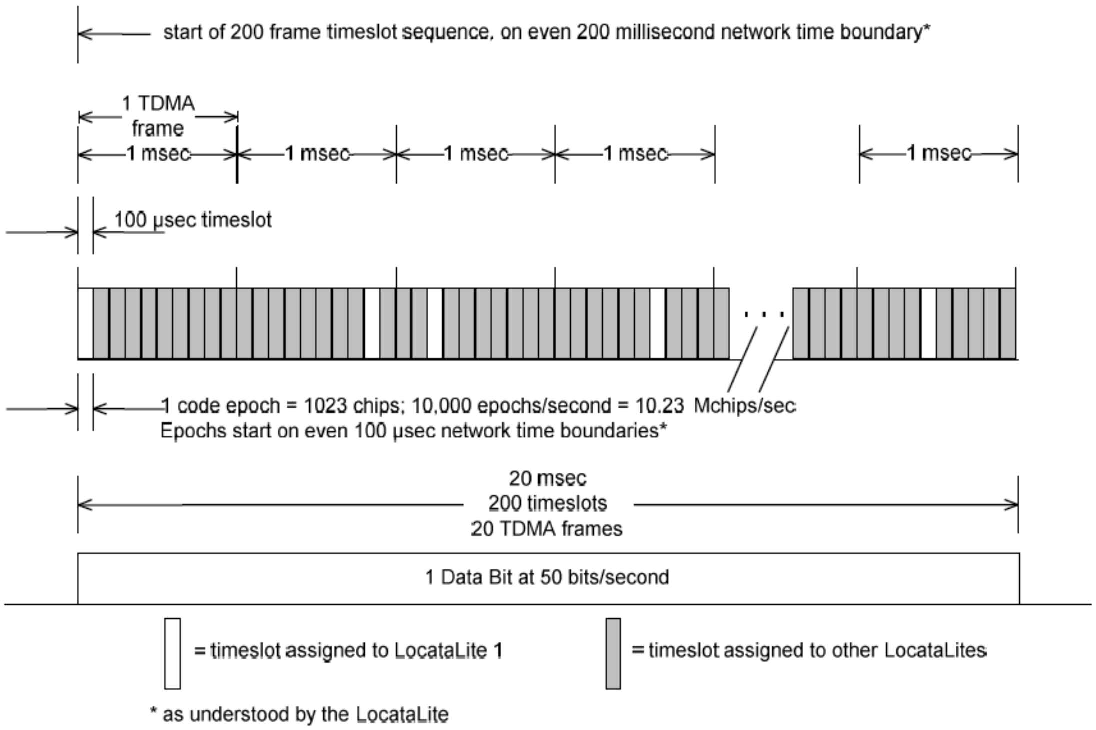

Figure 16: Locata / UHARS TDMA Architecture (Locata Corporation 2011)

A complete Locata Network is divided into SubNets made up of up to 10 LocataLites each. There are enough unique PRN codes defined in the Locata Interface Control Document (ICD) to accommodate 5 SubNets without the potential for overlap. As long as each SubNet remains geographically separated, PRN codes could be duplicated if more than 5 SubNets are required. Figure 17 illustrates the myriad of ways in which a LocataNet and its SubNets may be related. In any LocataNet there is one master reference which carries its own time reference or is fed an external (commonly derived from GPS) time reference updated at 1Hz. The remaining

LocataLites in the network become slaves to the master LocataLite via TimeLoc. Note in Figure 17 that subnet 2 has cascaded the TimeLoc synchronization one level. 9 LocataLites in subnet 2 are slaved to an intermediate master. All LocataLites in Subnet 3 are slaved to a single slave LocataLite in Subnet 2. All LocataLites in Subnet 4 are slaves to the original master LocataLite in Subnet 1. The Master-Slave relationship is independent of the subnet structure of a LocataNet. Master-Slave relationships would likely be determined by the most efficient means of connecting all LocataLites with the fewest number of TimeLoc hops. Subnet relationships are carefully determined during initial setup to ensure dynamic separation of LocataLite signals and will determine the assignment of PRN codes and TDMA slot assignments for each LocataLite.

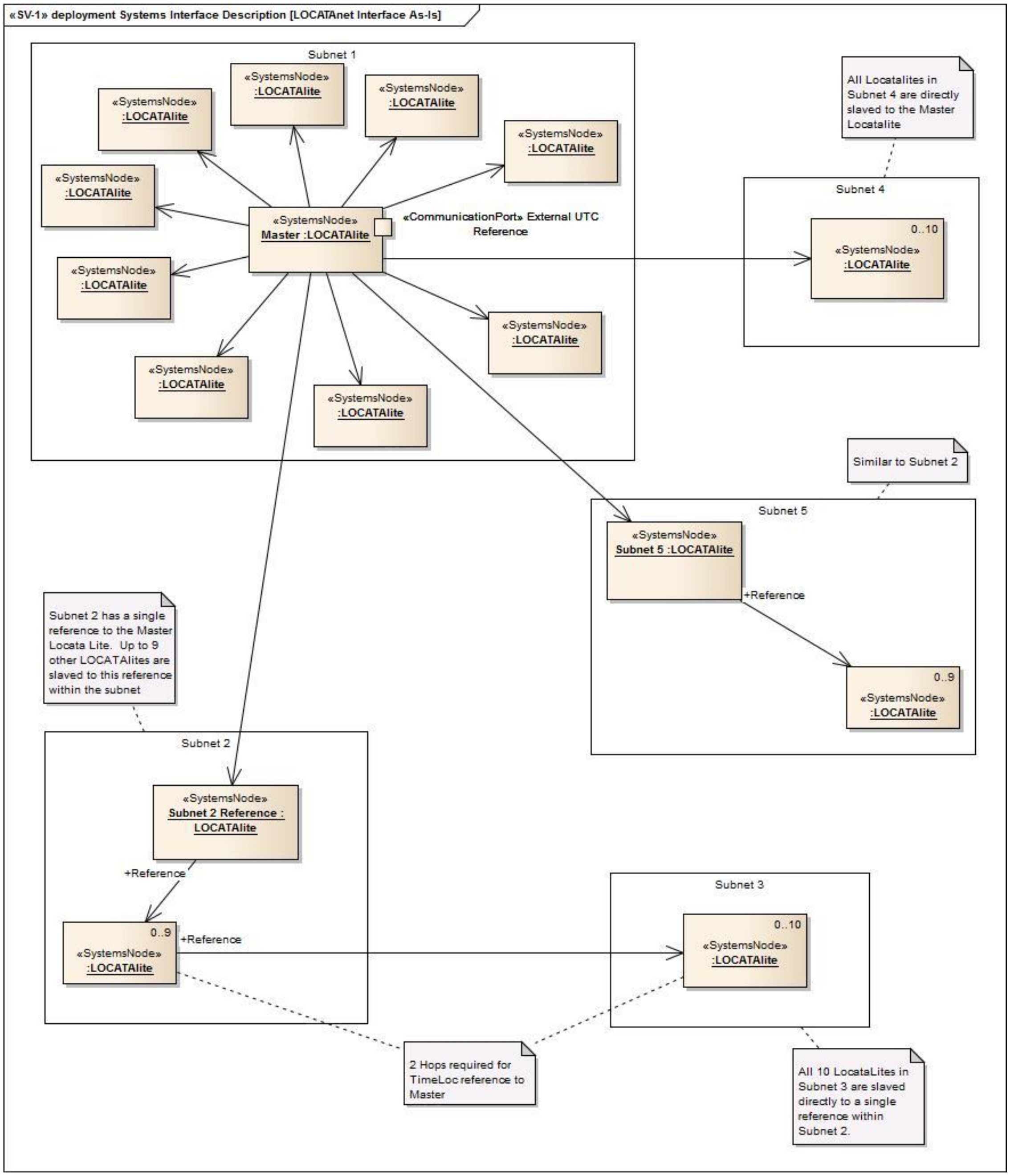

Figure 17: LocataNet TimeLoc Architecture

Figure 18 illustrates the connectivity between LocataLites and user positioning Receivers. In this particular network, NavSignal 3 comes directly from the master LocataLite. NavSignals 1, 2, 4, and 5, come from LocataLites that are TimeLocked to the master. NavSignal 6 comes from a LocataLite that is separated from the master and requires TimeLoc to be cascaded via Slave 4. This APNT receiver is receiving ranging signals from 6 LocataLites: an over-determined solution.   To determine a user's position, the Locata Receiver requires a minimum of four LocataLite signals. Three signals to solve for position in 3 dimensions and a fourth signal to solve for the receiver's clock uncertainty. Reception from a fifth LocataLite creates an over-determined solution can be used to detect false signals or erroneous signals. GPS receivers use these over-determined solutions for Receiver Autonomous Integrity Monitoring (RAIM).   This added integrity is required for use during approaches. Over determined solutions are not difficult to come by when utilizing a GNSS. Having 10-12 satellites in view and tracked is not uncommon.   Pseudolites present a much greater challenge because the likelihood of having many signals in range and in view is lower. To reduce the number of required pseudolites in view the role of integrity monitoring is shifted from the receiver and barometric altitude measured at the aircraft is used to aid the solution. This will allow an APNT pseudolite receiver to provide a position fix and receiver clock correction with only three signals. This diagram does not depict that each LocataLite actually transmits the same coded signal on two separate carrier frequencies, each from a physically separated antenna, for multi-path interference mitigation. This duplicity is removed from the diagram for clarity as it does not lend to an over-determined position.

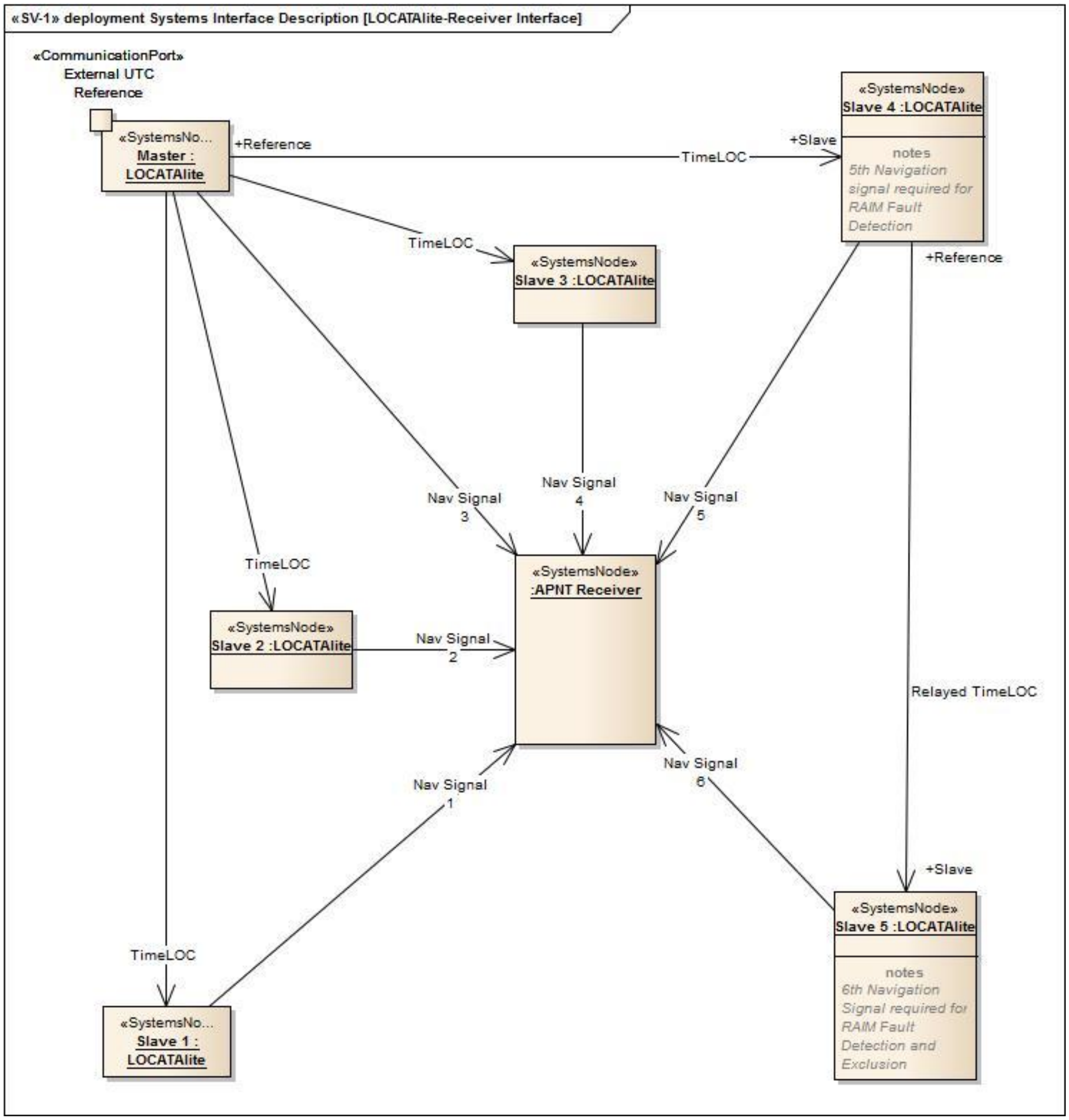

Figure 17: LocataLite Signal Connectivity

Signal Properties and Spectrum Usage

This section will cover several properties of the Locata and UHARS ranging signals and their effect on ranging performance. Many of these properties could remain the same if Locata is scaled up to meet APNT requirements while a few may have to change. Locata was developed as a commercially available positioning system and meets certain constraints that would not apply to an APNT system.   Of course, APNT brings along its own requirements and constraints. Three primary differences to keep in mind when reading the following section are as follows.   First, Locata and the UHARS operate in the 2.4-2.5 GHz Industrial, Scientific, and Medical (ISM) band. This band does not require a license to operate but must accept interference from other users and places limits on the power that can be transmitted. APNT will operate in the ARNS band that does not directly limit power output but does require new systems to operate on a non-interference basis. Secondly, APNT will cover much greater ranges. Locata was designed to operate indoors or in urban environments at ranges of less than a mile. APNT will almost certainly require signals to be effective at 100 nautical miles or more so that the number of pseudolites required is affordable.   Thirdly, APNT system accuracy requirements can be relaxed from centimeters to nearly 100 meters.

Locata was modeled after the GPS. This is evident in the opening paragraphs of Locata's ICD. The direct sequence, bi-phase shift keying spread spectrum signal was modified to fit into the 2.4GHz ISM band. The data stream was modified to accommodate stationary pseudolites. And the number of PRN codes in use was increased to accommodate an increase in signals on the network, although the method of generating each PRN code remains the same.

Carrier Frequency

The carrier frequency chosen for Locata and UHARS, as stated above, was confined to the 2.4 GHz ISM band. LocataLites each transmit two signals, differentiated by carrier frequency and PRN code, from each antenna (usually two) for multipath mitigation. The two carrier frequencies chosen for Locata and UHARS are 2414.28 MHz (S1) and 2465.43 MHz (S6). These frequencies were chosen partly for their convenient relationship to GPS carrier frequencies. A baseband oscillator used in any GPS receiver will have a frequency of approximately 10.23 MHz (f_B). GPS L1 at 1575.42 MHz is 154 times the base oscillator. Locata S1 is 236 times f_B, Locata S6 is 241 times f_B. Keeping receiver frequency plans as similar as possible can reduce cost and complexity of receivers designed for dual use. The analysis in this thesis limits carrier frequency choices to multiples of 10.23 MHz.

APNT will operate in the ARNS band between 960 MHz and 1215 MHz. The myriad of systems already occupying this band is covered in Chapter II of this thesis. The design of an APNT signal will have to fit within the ARNS band without interfering with other systems. Accommodations could be made for a new APNT signal, such as removing specific DME channels from widespread use, or limiting the transmission power at certain sites. This was done for the addition of GPS L5 when seven channels of JTIDS/Link 16 were marked for operation on a non-interference basis. Figure 19 illustrates the complexity of the ARNS band. In this figure each column represents the center frequency of an occupied channel. Signal properties such as data overlays or spreading codes will “widen” these channels. The magnitude of each column is only to represent the related system and usage, not the relative power density or any kind of priority.   For example, all DME Ground reply channels are approximately the same height for easier identification and those channels recommended for removal are slightly shorter.

Figure 19 reveals a few unoccupied or less frequently used bands that should be considered for APNT use. The most prominent gaps are those within DME channels to accommodate ATCRBS. The ATCRBS signal has a data overlay that spreads the signal and interferes with DME signals that might broadcast within +/- 10 MHz of 1030 or 1090 MHz. DME channels are paired for air-ground interrogation and ground-air reply. They are also paired for air-air usage by the military and for VORTAC, TACAN, and ILS usage. These relationships have left a few channels less frequently used even though they are not adjacent to ATCRBS. This means that allocating a specific frequency to a new APNT system may affect more than one system and more than one channel.   Minimizing these impacts should be considered. The FAA has designated certain channels of DME as “uncommon”. The DoD has designated approximately the same channels for mobile TACAN use which, at least domestically or for long periods of time, would be in uncommon usage. These uncommon channels are the shortest in Figure 19.   Usable gaps occur at 960-977 MHz, and 1147-1156 MHz. 1147-1156 could be expanded to nearly 20 MHz by eliminating DME channels 70x-76x. Because the paired frequencies of 1094-1100 MHz are adjacent to 1090 MHz, these channels are in less common usage. 107 paired VORs would be affected in the NAS today if these 7 channels are removed. This bands proximity to GPS L5, a low power signal, makes it less desirable. DME channel associations and pairings are described in detail in the National Aviation Standard for VOR/DME/TACAN (FAA 1984). DME channels 49x-59x could be eliminated and free up 1010 MHz to 1020 MHz. This 10 MHz band is less desirable because of its proximity to 1030 MHz ATCRBS. The third potential availability lies between 960 MHz and 977 MHz. This 17 MHz band lies between the bottom end of ARNS and the UAT at 978 MHz. It is occupied by the DME portion of TACAN channels assigned to mobile TACAN, three JTIDS channels, and one DME channel assigned to facility and equipment maintenance on the ground. Frequencies adjacent to 960 MHz could potentially be affected by systems outside the ARNS band. The effects of cell phone operations at 950-960 MHz can have an effect on DME channels below 970 MHz (Electronic Communications Committee, CEPT 2007). The UAT system operating at 978 MHz bounds the other end of this potential window. UATs will exist on nearly every aircraft as the primary means of transmitting and receiving ADS-B. They will also operate at nearly 800 sites across the NAS as ADS-B GBTs. There seems to be a consensus that this band from 960-977 is the most likely choice for any addition to the ARNS band (STAR 2006) (Lo, Pseudolite Alternatives for Alternate Positioning, Navigation, and Timing (APNT) 2012) (ICAO 2005). The following sections of this thesis will consider the performance of a UHARS like APNT signal in the 960-970 MHz band.

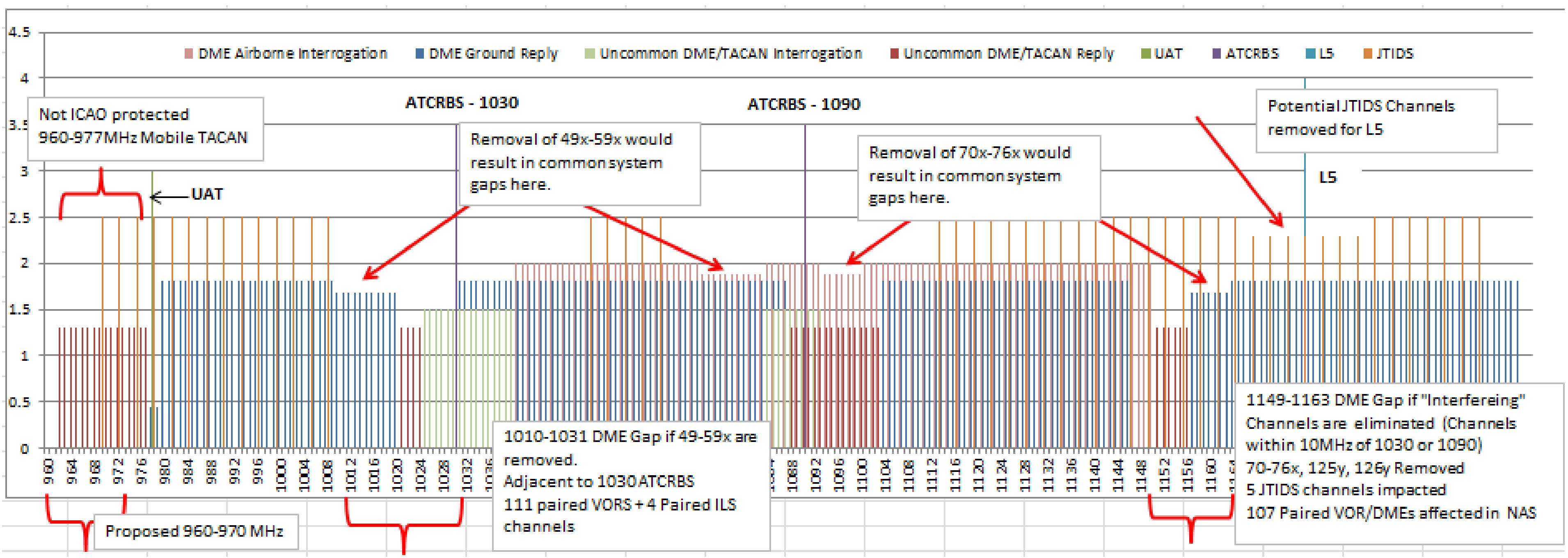

Figure 18: ARNS Band Usage

Spreading Codes and Chipping Rate

Locata utilizes a direct sequence bi-phase shift keying (DS-BPSK) spreading code. The direct sequence codes (PRN codes) are the same codes used by the GPS with the addition of codes to accommodate up to 200 unique channels on a LocataNet. The chipping rate of Locata and UHARS code is ten times faster than the GPS. Increasing the chipping rate to 10.23 Million chips per second spreads the signal wider but also increases the theoretical accuracy of the code tracking delay lock loops in the receiver. Because the ARNS band is quite crowded a high powered wide-band signal would be more difficult to integrate. Reducing the chipping rate, at the expense of accuracy, is one way to reduce the interference of an APNT signal on neighboring ARNS systems. Changing the format of the spreading code, other than the chipping rate, was not considered in this analysis.

The chipping rate of a DS-BPSK signal is related to the signal's power spectrum density (S) in Equation 1. Band pass filters at the transmitter and receiver can generally mask all but the main center lobe. Therefore, the minimum "bandwidth" of any signal is about twice the chipping rate. Figure 20 is a PSD plot of the UHARS signal at the transmitter antenna. Reducing the chipping rate will make the lobes of this plot taller and skinnier. The bold green line represents the masked signal when an 8-pole 20 MHz band pass filter is applied. The masking filter minimally affects the power contained in the main lobe of the signal but can reduce power transmitted by 60 dB only 10 MHz from the center frequency. The masking filter is derived from the band bass filter used in the UHARS demonstration manufactured by L-Com, model number BPF24-809.

$$S = P_T T_C\{sinc[(f - f_C)T_C]^2 + sinc[(f + f_C)T_C]^2\}Watts/Hz \tag{1}$$

$$P_T = Power\ Transmitted\ (watts)$$

$$T_C = chip\ duration\ (seconds)$$

$$f = frequency\ (Hz)$$

$$f_C = carrier\ center\ frequency\ (Hz)$$

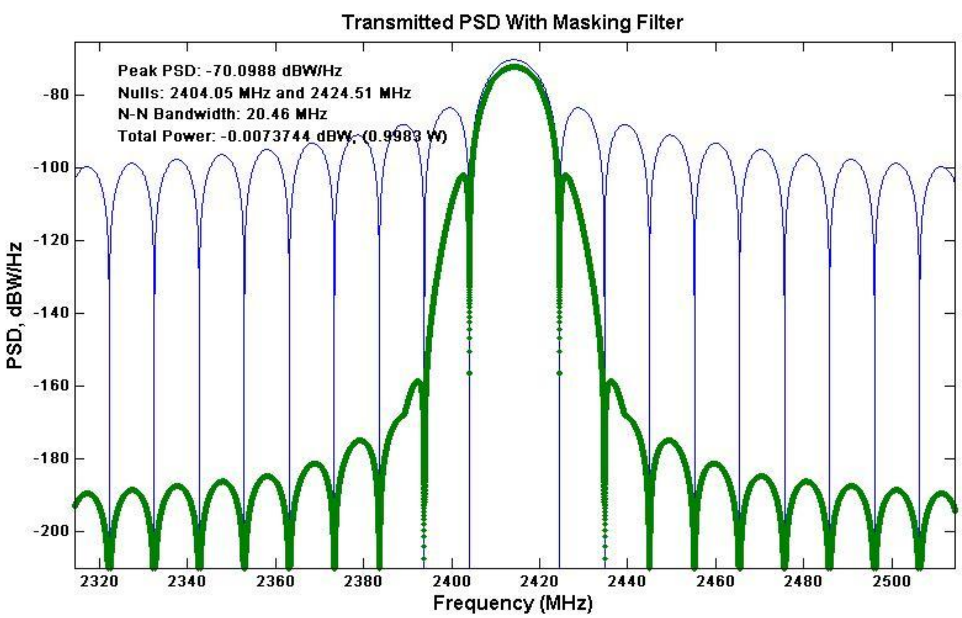

Figure 20: UHARS Transmitted Signal

The delay lock loop (DLL) of a receiver tracks the phase changes in the signal generated with each chip. This method of "code tracking" is less precise than carrier phase tracking but is more robust. UHARS 3D RMS accuracy was reduced from about

18cm carrier solution to 25 cm code solution (Craig 2011). As chipping rate of the code increases the duration of each chip is reduced and precision is improved. The duration of each chip is converted to range when multiplied by *c*, the speed of light. Equation 2 relates chipping rate and received SNR to DLL pseudorange error. Note that T_C is directly proportional to the standard deviation of DLL error.

$$\sigma_{\Delta\tau} = cT_C\sqrt{\frac{d}{4(P_C/N_0)T}}\ meters \tag{2}$$

$$c = speed\ of\ light\ \left({}^{m}/_{s}\right)$$

$$d = receiver\ correlator\ spacing\ (chips)$$

$$\frac{P_C}{N_0} = Received\ signal\ power\ to\ Noise\ power\ density\ \left({}^{dB}/_{Hz}\right)$$

$$T = averaging\ time\ (seconds), {}^{1}/_{T} = DLL\ Bandwidth$$

Figure 20 illustrates the relationship between chipping rate, received signal strength, and DLL accuracy. Error values in the plot are 95% RMS, or 2σ. UHARS receivers generally receive -100 dBW to -130 dBW of power. In this plot, receiver correlator spacing is set to 1 chip, received white noise PSD is set to -150 dBW/Hz, and the DLL bandwidth is .005 Hz. At P_C = -130 dBW, the DLL accuracy is reduced to 1.75 meters, or doubled, if chipping rate is reduced to 5.115 MCps. Reducing chipping rate by as much as ten times, to 1.023 MCps, may still provide enough ranging precision to meet the 92.6 meter goal of APNT and significantly narrow the bandwidth of an APNT signal.

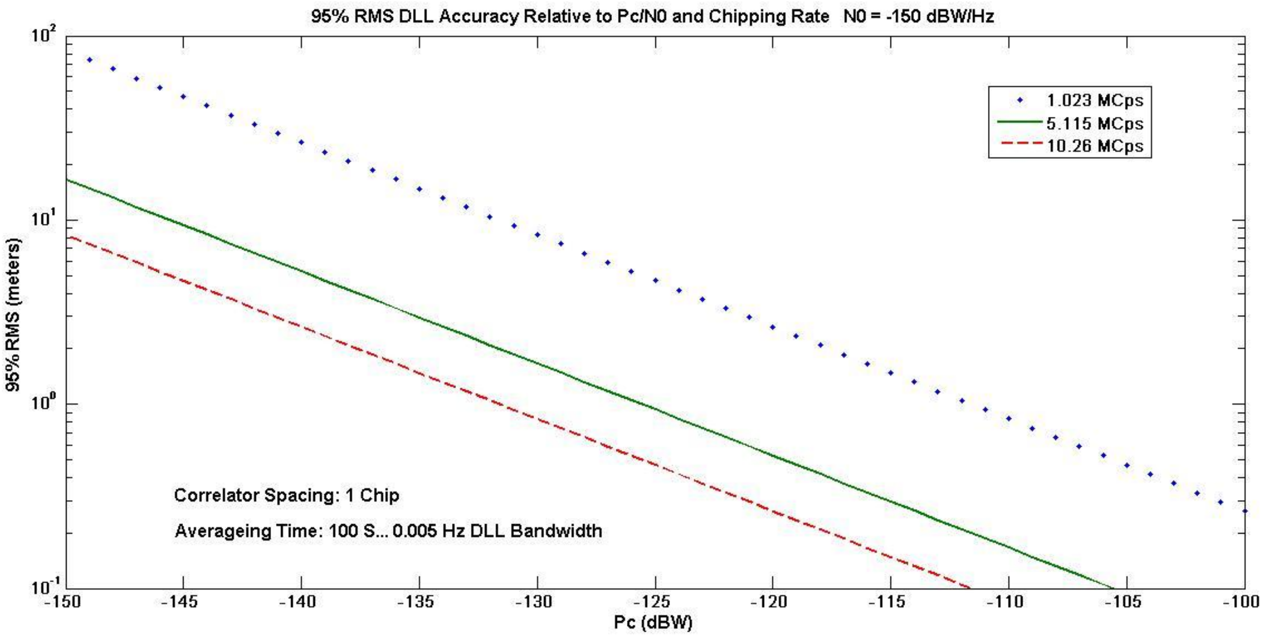

Figure 21: DLL Ranging Precision and Chipping Rate

TDMA and Receiver Dynamic Range

Figure 16 illustrates the TDMA scheme used by Locata and UHARS to overcome the near far problem. Each LocataLite is assigned a 100µs N-slot during every 1ms TDMA frame. During each subsequent 1ms TDMA frame the LocataLite will transmit during a different N-slot based on a pseudo-random schedule. This pseudo-random pattern ensures that clock errors between LocataLites would not otherwise cause overlapping transmissions to occur repeatedly. The TDMA slot assignments repeat every 200ms.

At a chipping rate of 10.23MCps, an entire 1023 chip PRN code is transmitted in one 100µs N-slot. At a data rate of 100 bps, ten complete code epochs are received in the duration of each bit. The integer ratio of cycles to chips, chips to code epoch, code epoch to TDMA slot, and TDMA slot to data bits is not mandatory in the design of a receiver. If these integer relationships are altered by, for example, halving the chipping rate so there are 511.5 chips per TDMA slot, the receiver acquisition and tracking capabilities should be evaluated in future research.

By assigning each LocataLite on a subnet a unique TDMA slot, up to 10 LocataLites can be in the same geographic area and significantly varied ranges from the user receiver and not interfere with each other. Because there is some cross correlation between the PRN codes of each LocataLite, a receiver could misinterpret a PRN code if its received signal is more than 23dB from other pseudolites. This 23dB separation between cross correlation peaks could be increased to 33dB of separation by increasing the code lengths to 10230 chips, as was done in the new GPS L5 signal (Enge 2003). It is not unreasonable to imagine an aircraft flying only a few thousand feet above an APNT pseudolite, or a range of about .5nmi. At .5nmi from pseudolite A the APNT receiver would have trouble distinguishing pseudolite B if it was more than 8nmi away. This would severely limit the service volume of each pseudolite and the number of pseudolites required to cover all APNT zones. 33dB of separation might provide 20nmi maximum range but this is still unacceptable for APNT.

The cost of this TDMA scheme is accumulated power of the received signal at the Locata receiver. Because the LocataLite is only transmitting 10% of the time, the accumulated energy is 10% of a continuous transmission. In other words, to the Locata receiver, a LocataLite transmitting 10W for 100µs of each ms appears to be transmitting at only 1W. This becomes a challenge when interference with neighboring systems is considered. For example, a UAT on the ground broadcasts its entire message during 5 to 10ms of each second. To the UAT, a LocataLite is transmitting at 10W for 20% of this time which is likely to cause enough interference to be considered continuous transmission. A UAT must be capable of tolerating co-channel interference of -86dBW if pulsed as a DME signal, or up to 3600 3.5μs pulse pairs per second, , but only -131dBW if continuous (MILSTD-291C 1998). Increasing the duration of a TDMA N-slot to 200μs and reducing the number of slots in a frame to five would double the accumulated energy at the Locata receiver without adversely affecting nearby UATs. It would, however, reduce the number of possible LocataLites in a geographic subnet from 10 to 5.

Power & Service Volume

Transmitted power will have the greatest effect of any signal characteristic considered in this thesis on the effective range, or service volume, of an APNT pseudolite. LocataLites for commercial use are restricted to 1W transmission in the 2.4GHz ISM band. UHARS received a waiver to transit at up to 10W on the White Sands range. The ARNS band places no blanket restrictions on transmission power. The maximum transmission power levels of each system are uniquely defined to prevent unwanted interference. Minimum transmission power is determined in order to provide a guaranteed service volume for each system. This service volume will partly determine how many pseudolites are required to cover all APNT zones.

UHARS pseudolites transmit 10W at 2.414 and 2.465GHz. Testing at Holloman indicated a service volume with a radius of approximately 30nmi and up to at least 25,000 feet. Many of the legacy navigation aids in service today provide service out to 130nmi. For ease of comparison, a service volume with a 40 nautical mile radius up to 18,000 feet and 130nmi from 18,000 feet to 45,000 feet is considered.

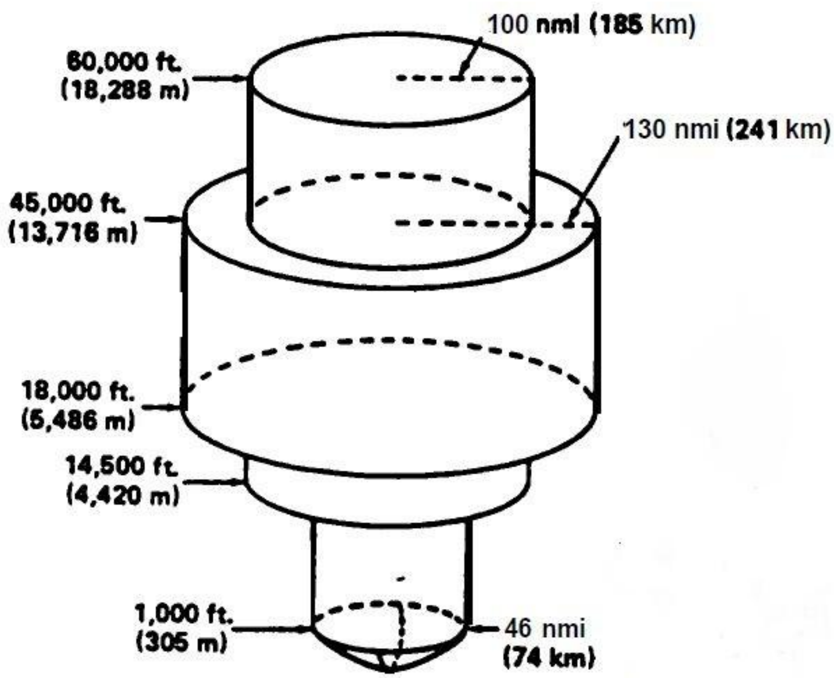

Figure 19: Standard Service Volume-High

To increase the service volume of an APNT pseudolite power will have to increase. A significant increase in service volume already comes from reducing the carrier frequency of the navigation signal. The effective area of the receiver antenna is related to the square of the carrier wavelength as shown in Equation 3.

$$A_E = \frac{G_R \lambda^2}{4\pi} m^2 \tag{3}$$

$$G_R = Receiver\ antena\ gain$$

$$A_E = Effective\ antenna\ area\ (m^2)$$

If transmitter power remained at 10W and f_C is reduced from 2414 MHz to 971 MHz, the same power is received at 75nmi as was received at 30nmi. Received power, user range, and carrier frequency are related in Equation 4.

$$P_S = \frac{P_T G_T G_R}{L_A 4\pi R^2} \frac{c^2}{4\pi {f_C}^2}\ watts \tag{4}$$

$$P_S = Power\ Received\ (watts)$$

$$G_T = Transmitter\ antenna\ gain$$

$$L_A = Atmospheric\ propagation\ loss$$

$$R = Range\ (m)$$

$$\lambda = carrier\ wavelength\ (m)$$

To acquire and track a signal from a UHARS LocataLite, the minimum received power for a UHARS receiver is approximately -130 dBW (Craig 2011). AGPS receiver certified for precision approach use will acquire a signal with a minimum power level of approximately -150dBW. This is a significant difference in receiver sensitivity. Based on Equation 4, an improvement of 20dB in receiver sensitivity could increase the range of the UHARS signal to over 200nmi without any increase in power or modification to the signal. An increase in the sensitivity of Locata receivers for the purpose of APNT could be studied in future work. This thesis assumes that any APNT system modeled after Locata and the UHARS would have to demonstrate feasibility without significant modification to receiver capabilities.

Antennas and Filters

The antennas chosen for a new APNT system will affect the predicted service volume of each pseudolite as well as their influence on other systems in the ARNS band. The antenna pattern chosen for ground transmitters will likely be isotropic in the horizontal plane but will concentrate power between the horizon and approximately 60 degrees above the horizon. Legacy navigation systems such as VOR and DME generally do not provide reliable reception above approximately 40 degrees. Figure 23 illustrates the vertical antenna pattern of a commercially available broadband antenna used for Mode-S squitter and ADS-B transmissions (dB Systems Inc. 2012). To be conservative, an antenna with gain pattern that is isotropic in azimuth and uniformly spread between -10 degrees below the horizon is applied. This results in a transmitter gain of 2.3dB. A gain of 10dB or more could significantly increase the range of a UHARS pseudolite and is not unrealistic, although a corresponding increase in interference to nearby systems would also be felt. Because fixed navigational aids are not power limited like satellites or LocataLites, antenna gain is more useful for directing energy where it is desired rather than simply increasing effective range.

The antenna pattern chosen for the aircraft receiver in the UHARS demonstration was a custom designed quadrifiliar helix antenna. A monopole antenna or blade on the belly of an aircraft would have limited reception range in the vertical axis. A patch antenna on the belly of the aircraft would severely limit the horizontal range of the UHARS network. The custom helical antenna offered sufficient gain in the vertical axis to receive pseudolite ranging signals below the aircraft without compromising horizontal gain. Reception of pseudolite signals below the aircraft is important for maintaining good geometry when determining altitude. Because APNT may rely on barometric altitude for vertical positioning a standard monopole antenna may be sufficient. A study by RTCA on appropriate aircraft antennas for ADS-B UAT usage determined that a 5/8 λ monopole antenna could provide approximately 5dB gain in the horizontal plane (UPS Aviation Technologies 2001). While gain in the vertical axis might be significantly less, a UHARS signal at 20W would only require a receiver gain of -5dB to reach a pseudolite 55,000' directly below it. The ability to use existing antennas for dual purpose could simplify the installation of new APNT hardware on aircraft. A receiver antenna with an isotropic gain of 5dB is assumed in this analysis.

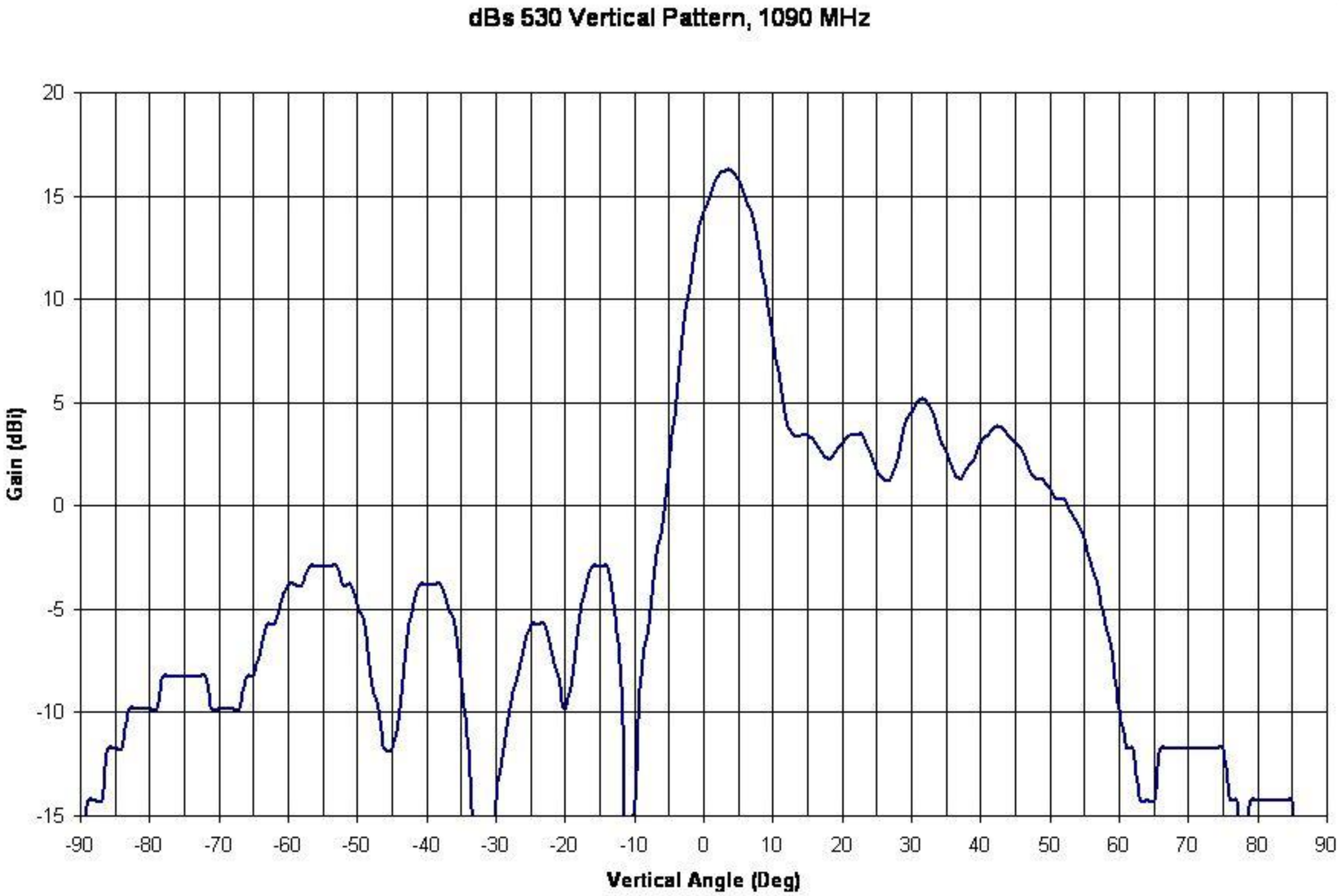

Figure 20: Ground Transmitter Antenna Gain

Adding a bandpass filter to any broadband signal will significantly reduce the amount of interference received by neighboring systems. An APNT signal in the 960-970 MHz range must be masked appropriately to avoid interference with systems below 960MHz or the UATs that operate at 978MHz. An APNT pseudolite broadcasting a given signal will have a minimum standoff range from any UAT to avoid interference. Because there will be over 800 ground based UATs and countless more airborne UATs operating in the NAS, minimizing the standoff distance is important. Figure 24 illustrates a potential APNT signal modeled after the UHARS and operating *without* a bandpass filter. As power transmitted by the pseudolite is increased in the Y axis, the effective range of the pseudolite increases on the X axis, but so does the minimum standoff distance from a UAT to avoid interference. In this model the chipping rate is reduced to 5.115MCps to narrow the signal. The TDMA slot is increased to 200ms to increase the received code power at the pseudolite. The center frequency is placed at 971MHz. Lowering the center frequency may require concession from users outside the ARNS band. Even with these modifications, an APNT pseudolite powered to reach 130nmi would have to remain 20nmi from the nearest UAT; an impossible requirement. Applying a bandpass filter can reduce this minimum separation to just a few meters.

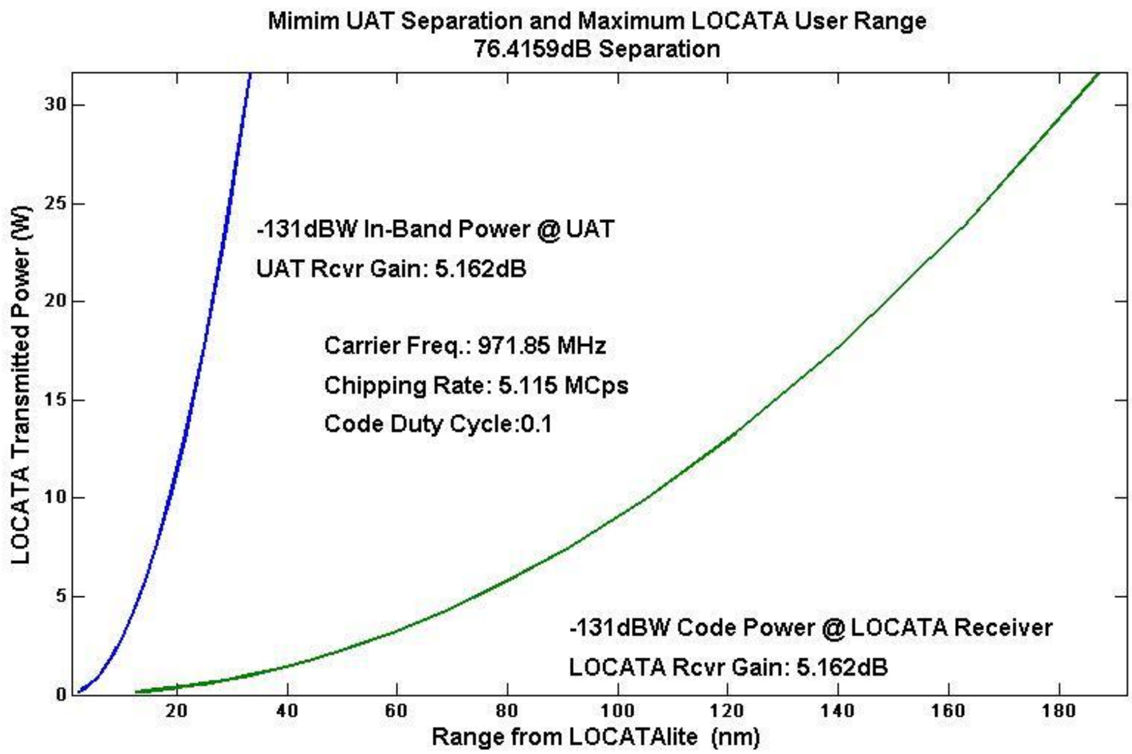

Figure 21: Pseudolite-UAT Separation, No Filtering

Network Size and Performance

In 2012 the MITRE Corporation was funded to conduct a study on DME/DME based RNAV coverage of CONUS (Niles, et al. 2012). The objective was to determine if current DME sites provide sufficient coverage of CONUS airspace to meet RNAV 1.0 requirements. Where there are gaps in DME coverage or unnecessary sites existed they were indicated. The methods used in this study could be applied to determine the number and location of pseudolites necessary to cover all APNT Zones.

The first step in the MITRE study was to model DME/DME RNAV requirements. RNAV 1.0 requires a 1-σ Horizontal Position Error (HPE) of .866nmi (FAA 2005). A Horizontal DOP (HDOP) was assumed to be 2.82. Maximum User

Range Error (URE) is then approximately .3nmi. For APNT, the requirement for 2-σ HPE is 92.6m. If an HDOP of 2.82 is assumed, maximum URE is 16.3m. DME/DME RNAV only requires two DME sites to determine a receiver position. A pseudolite analysis should include three pseudolites or more in any position fix (≥4 if barometric altitude is not incorporated). The sensitivity of coverage to the number of solutions required was explored in 2010 by Sherman Lo, et al (Lo, Pseudolite Alternatives for Alternate Positioning, Navigation, and Timing (APNT) 2012). Interestingly, coverage at 5000' AGL (Zone 2) was not significantly improved when only two signals are required. The mountainous areas of the western United States remain poorly covered in either case. Use of a DME site is restricted to ≥3nmi, ≤130nmi and ≤40^{o} elevation angle. As a starting point, 130nmi maximum range can be modeled. The restrictions on minimum user range and elevation angle can be lifted. The MITRE study modeled Zone 3 cones over the busiest 65 of the 135 airports listed in the APNT CONOPS. A complete pseudolite analysis should cover all 135 airports. 920 DME sites were considered in the MITRE model. Because APNT Pseudolites could be most conveniently placed at existing FAA sites a pseudolite coverage analysis should include these 920 DME sites as well as any VORs located without DME. Finally, "users" were modeled in a 4 nautical mile grid pattern over all of CONUS. The altitude of each user was determined by the lower of 18,000' MSL enroute, or the bottom of a Zone 3 cone at the user's location, taking into account minimum IFR altitudes of 1000' or 2000' AGL. Terrain masking effects that restrict line-of-sight between the DME site and user were considered as they should be when evaluating APNT. The differences between the MITRE evaluation of DME for RNAV and pseudolites for APNT are summarized in Table 5.

Table 5: DME RNAV vs Pseudolite APNT Constraints

Constraint	DME RNAV	Pseudolite APNT
Airports with Zone 3	65	135
User Spacing	4nmi	4nmi
Max. URE	555m	16.4m
Min. # Transmitters	2	3
Max. PDOP	2.82	2.82
Service Volume	3-130nmi according to receiver height	0-130nmi according to receiver height above ground
Max. Elevation Angle	40^{o}	90^{o}
Min. Receiver Altitude	18,000’ enroute >1000’ AGL in Zone 3	Zone 2 enroute >500’ AGL in Zone 3

Given the above constraints, each user’s location was evaluated to determine if a valid DME/DME position fix would be possible. The current DME network provided a valid fix to 98% of CONUS airspace. Varying the minimum altitude used in a Zone 3 approach up to 2000’AGL from 500’ AGL improved coverage to 98.33%. When the DME network was evaluated assuming repair to all low altitude DMEs and repair to all restricted DMEs, coverage increased to 99.14%.

To determine the size requirements of a future DME RNAV system, MITRE modified their model to require 100% coverage of CONUS and asked the question: How many DME sites will be required and where should they be placed? 920 DME sites, 4572 public airports, and 258 additional new sites were considered in a Voronoi process. After two passes a minimum network of DMEs that included new sites, and the removal of unnecessary sites was determined. A total of 491 sites were required to cover all of CONUS if Zone 3 service does not go below 1000' AGL. An additional 26 sites were required to expand Zone 3 coverage to 500' AGL. Although many ILS intercept altitudes are well above 1000' AGL, an analysis of APNT pseudolites should require coverage as low as 500' AGL. The APNT requirement for three pseudorange measurements to determine a fix could have a significant impact on the number of sites required for pseudolite coverage. Increasing the number of Zone 3 airports will also increase the number of pseudolites required for complete coverage.

Tropospheric and Multipath Errors

UHARS and other pseudolite signals propagate through the Troposphere for significantly greater ranges than a GNSS. Because light travels slower through the troposphere (especially wet troposphere) the ranging signal is delayed and interpreted by the receiver as a longer than actual range. Pseudolites benefit from not having to transit the ionosphere which can be significantly more difficult to model. Locata has incorporated a tropospheric error modeling algorithm that was first applied in simulation at AFIT in 2003 (Bouska 2003). This model was used in the UHARS demonstration at White Sands in 2011.

To accurately model and account for tropospheric errors several variables are considered. Most of these variables will already be known by any pseudolite once a position fix is determined. Additional measurements are required at each LocataLite for atmospheric pressure, air temperature, and relative humidity. Collecting the same additional measurements at the receiver will benefit the user. Fortunately these data are easy to collect on the ground and are already collected at many of the proposed pseudolite sites.

If not corrected for, tropospheric delay could induce as much as 120m of error over 130nmi into each pseudorange measurement. The model derived in Bouska's thesis has been improved upon in Locata and UHARS work. Locata networks today can reduce residual tropospheric error to about 1% of actual. A worst case estimate for residual tropospheric error is then assumed to be 1 meter or less at 130nmi, or about 4 parts per million. The current methods applied to UHARS and Locata are compatible with the APNT solution.

Multipath error is mitigated in Locata Networks with the addition of a second carrier frequency and antenna at each LocataLite. The two antennas are placed approximately 10 meters apart at each UHARS LocataLite. For the longer ranges required by APNT, this separation might be increased. Each antenna transmits the two carrier frequencies, requiring four distinct PRN coded signals at each LocataLite. In the crowded, or indoor environments typical of Locata installations multipath can have a significant impact on availability when destructive interference causes receivers to lose lock. Thoughtful installation of pseudolite antennas could offset the need for multiple ranging signals from each pseudolite. Further research on this topic is necessary. Multipath error can be bounded as a function of code chip duration and correlator spacing in the receiver as shown in Equation 5 (Misra and Enge 2001). This is hardly a consolation because a signal with a chipping rate of 10.23MCps like the UHARS could see multipath error as large as 45 meters.

$$\Delta\tau_M = cT_C(1 + d/2)\ meters \tag{5}$$

A Proposed Signal and Predicted Performance

The sections above describe several variables in the UHARS signal that could be modified to meet APNT requirements. MATLAB was used to efficiently manipulate these variables and to determine the effective range and ranging accuracy of any proposed pseudolite signal. Equations 1, 2, 4, and 5 were used to model the signal. The CDMA and TDMA patterns of Locata were not significantly changed. Table 6 lists the variables used to estimate performance of an APNT signal. Table 7 lists the outputs of the model.

Table 6: Proposed Signal Variables

Variable	UHARS	Proposed Value
f_B	10.23 MHz	10.23MHz
f_C	2241 & 2465 MHz	971.85 MHz
Chip Rate	10.23 MCps	5.115MCps
Code Length	1023	1023
TDMA Slot Duration	100µs	100µs
Data Bit Rate	100	100
Transmitted Power	10W	20W
Transmitter Antenna Gain		2.3dB
Receiver Antenna Gain		5.162dB
User Range	15 nmi	130 nmi
Transmission Mask	20MHz Bandpass	6MHz Bandpass
N_0 ***– Noise background***		-150dBW/Hz
Maximum PDOP	2.838	2.838
Max Correlator Spacing		1
Minimum Received Code Power	~ -135dBW	-132dBW

Table 7: Estimated Signal Accuracy

Measure	Performance Value
95% RMS DLL Error	.74 meters
Residual Tropospheric Error	2 meters
Local Timing Synchronization Error (Single TimeLoc hop)	.6 meters
95% RMS Position Accuracy $(\boldsymbol{PDOP \cdot \sqrt{DLL^2 + Tropo^2 + \Delta\tau^2}})$	6.3 meters

The model also included an analysis of received signal by other systems in the ARNS band. Each system has a specified level of interference it's receivers must be able to tolerate. DME, UAT, and 1030 ATCRBS, and JTIDS each specify approximately -130dBW continuous co-channel interference. Each system also specifies a minimum receiver rejection level for out of band interference. If a 4MHz wide band is assumed, the maximum received PSD for any system is -196dBW/Hz. The model was run at varying center frequencies, chipping rates, transmitted power levels and user ranges to determine the effects on each neighboring system. The values above produced a signal that meets the 92.6m accuracy requirement and appears to fit within the ARNS band. Figure 25 shows the received PSD of a proposed APNT signal at three different center frequencies. The solid line PSD plots represent the power arriving at a receiving antenna at 100m from the transmitter. Interference levels drop as the receiver and offending transmitter are separated further. A band pass filter has been applied at the transmitter, but no receiver filtering is accounted for. A rough estimate of acceptable interference level is the horizontal dashed line at -196dBW/Hz. -196dBW/Hz is the PSD of -130dBW within a 4MHz band. If the PSD plot of a proposed signal is above this line at any given frequency then interference may be a problem. The vertical bars represent each ARNS system channel in use and do not imply power or bandwidth occupied. The dashed lines of 1030 ATCRBS and GPS L5 illustrate the broadband nature of those signals. Figures 18 and 25 can be used in conjunction to evaluate a more desirable center frequency for pseudolite APNT. Note the proximity of the proposed APNT signal at 971MHz to the UAT transmitter at 978MHz. This is an area for further study if 971MHz is chosen. The UAT signal is only modulated at 1Mbps, making it a fairly narrow signal. The receiver mask applied to a UAT transmitter is -20dB down at +/- 1MHz and -5dB down at +/- 2MHz. UAT rejection ratios specified are similar. Applying the receiver rejection ratio to the model of the proposed APNT signal yields only -142dBW of received interference at the UAT from a pseudolite 100m away.

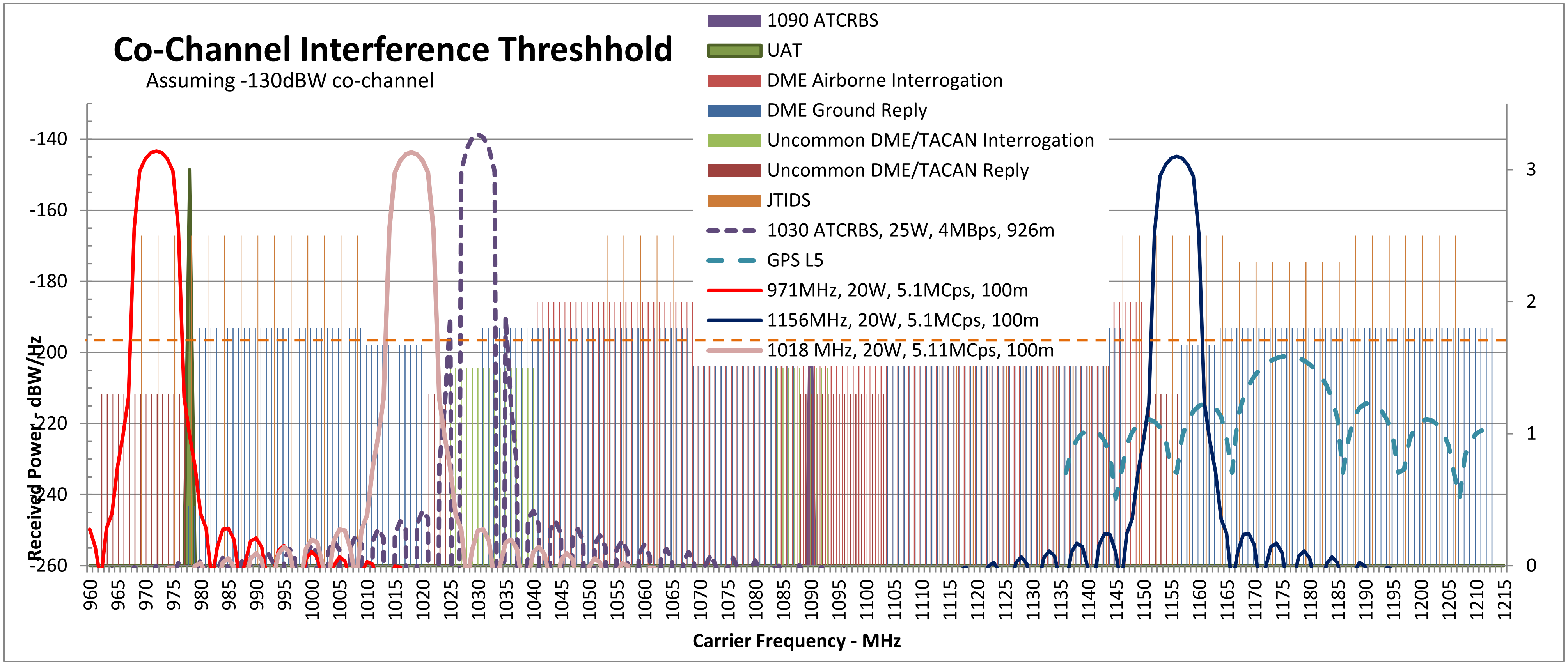

Figure 22: Co-Channel Interference Threshold

V. Conclusions and Recommendations

Conclusions of Research

AFIT was tasked by the FAA to answer the question: Could a pseudolite system similar to Locata and the UHARS meet APNT requirements by 2025? The question was answered through a systems engineering approach. A model of the proposed signal was built to evaluate its performance and enable modification for analysis of alternatives. Chapter III of this thesis describes the process used to connect NextGen OIs to APNT performance requirements and the pillars of APNT described in the APNT CONOPS. This process was indifferent to the technology or design of the APNT source chosen. Instead, it answers the question: Will the performance requirements laid out for a future APNT source meet NextGen Operational Improvements? Chapter IV takes a close look at the architecture of Locata and the UHARS to determine how UHARS could meet those APNT requirements.

63 operational improvements related to navigation, positioning, and surveillance were matched against APNT performance requirements. Nearly half of those OIs will not be fully enabled by APNT given the performance requirements and scope of APNT laid out in the CONOPs. The OIs that are not met relate to increasing capacity in terminal areas, providing access to secondary airports, positioning and surveillance on the ground, and flexibility in the terminal environment. If the threshold for accuracy is 185 meters, capacity would not be improved in many areas. Capacity is dependent on spacing and spacing is limited by surveillance capability. To meet or exceed current spacing minimums, APNT must support 3nmi separation by providing 92.6m accuracy.

An unexpected GPS outage would require significant workload increase on the part of controllers and aircrew to reposition aircraft to safe separation distances. If 92.6 meters is achieved, then surveillance performance will meet that of ATCRBS and ADS-B. A seamless transition from GPS to APNT is then possible in the event of GPS outage. APNT shortfalls are then the product of lack of coverage and reliance on ILS for recovery in low ceilings and visibility. Limiting APNT Zone 2 to 5000' AGL will restrict access to many secondary airports. The FAA should consider increasing the number of Zone 3 space, or potentially adding a fourth zone that would extend guaranteed APNT service to 1000' AGL over secondary airports. Locata technology has the flexibility to allow for an infinite number of pseudolites within the NAS, given no more than 50 are within view of a receiver at any time. Low powered pseudolites could be placed on the ground at busy airports to provide APNT positioning on the ground. I should be noted here that the cost of meeting or exceeding current RNAV standards with a APNT system may be prohibitive and unnecessary. As an alternative to GNSS, APNT, at a minimum, must allow safe recovery of aircraft in the event of GNSS outage. The cost benefit analysis may reveal that meeting all of the APNT pillars and NextGen OIs is not the prudent choice.

The APNT is not being designed as a time distribution service. TimeLoc is not suited to provide time synchronization over long ranges, meaning a UHARS derived APNT source would rely on an outside timing synchronization. Providing robust timing to a pseudolite network was explored by Lo, Akos, and Denis in 2012 (Lo, Akos and Dennis 2012). Their work shows that antennas designed to reject interference and jamming could provide a reliable link to space based time sources. This method is possibly affordable enough to provide reliable timing to pseudolites but jam resistant antennas may be cost prohibitive for many other users in need of a precision timing source. Given the explosion in creative use of the GPS for both position and time, it seems shortsighted to limit APNT design to only servicing well equipped aircraft above 1000' AGL.

A modified UHARS signal was proposed in Chapter IV that will provide better than 92.6m positioning accuracy at ranges up to 130nmi. With a modest power increase to 20W and a reduction in code chipping rate, the UHARS signal can match the service volume of today's navigation beacons and provide a position reference accurate to better than 10 meters. This level of accuracy allows for some design flexibility. For example, poor geometry and PDOP or network timing errors would not immediately push accuracy out of limits and requirements could be relaxed. Increasing power transmitted is not likely to significantly reduce the number of pseudolites required to cover all APNT Zones. Terrain masking and service at extreme elevation angles is more often a limiting factor. An analysis similar to that conducted by MITRE in 2012 could determine the most efficient location of pseudolites to cover all APNT Zones.

The modified UHARS signal could potentially fit into the crowded ARNS band provided. An infrequently used band from 960-977 MHz exists that could fit a well masked wide band navigation signal. The proposed signal is shown to be below the allowable interference threshold of its closest neighbor, the UATs used for ADS-B, when separated by 100 meters. The practicality of building transmission sites in the real world will have to be studied. Over 800 ground based UATs are planned throughout the NAS. Nearly all aircraft equipped for ADS-B will operate a UAT. Antenna choices and proximity of transmitters should be evaluated in future work. Any channel chosen within the ARNS will have its list of challenges but 971 MHz appears to be the least complicated.

Recommendations for Future Research

The first priority for future research should be a detailed service volume analysis similar to the DME study performed by MITRE in 2012. The input variables and their differences are described in Table 5. Chapter IV describes a candidate signal that could provide a service volume similar to VOR and DME sites. This signal can provide a starting point to determine if pseudolites placed at current VOR and DME sites would provide adequate coverage of all APNT Zones. Where significant gaps exist, the number and location of new signals required can be determined. Based on the shortfalls of APNT found in this thesis, future research could focus on the expansion of APNT Zones to the surface or an increase in the number of Zone 3 cones for approaches to secondary airports. The cost of expanding APNT service in numbers of pseudolites is an important factor.

Related to this task of evaluating pseudolite coverage, would be a systems engineering approach to expanding APNT service for non-aviation use. Positioning, and timing uses for GPS far exceed those originally required by the DoD. Thoughtful, flexible design has allowed the commercial benefits of GPS to far exceed its cost. If this approach is taken to APNT it may be applied to highway navigation, mobile communication, and time distribution on the ground. Research would attempt to answer the following questions. Could a Locata system be implemented on a national scale with large numbers of low powered pseudolites with service volumes similar to cellular phones? Could such a pseudolite network provide the integrity required for safety-of-life applications?

The second priority for future research should be a detailed simulation of candidate signals. Three channels for APNT were proposed in this thesis and roughly modeled against neighboring ARNS band signals. An APNT signal centered at 971MHz must not interfere with the UATs broadcasting at 978MHz, the DME channels that begin at 980 MHz, or the JTIDS channels as low as 970MHz. Broadcasting experimental signals in the ARNS band is a complex task. Simulation of the APNT signal as well as the UAT signals for interference analysis may be within the scope of a follow-on thesis.

A high fidelity model of any APNT signal might include pseudolite transmitter and receiver design. Recall that Locata was modeled from the GPS to facilitate integrated receiver design. The FAA will likely require that APNT receivers be installed on all aircraft that wish to operate in controlled airspace. Other users of APNT, especially non-aviation and non-commercial user would benefit from small, inexpensive receivers. Given a candidate APNT signal, could a single receiver be designed to track both APNT and GNSS signals? Smart phones, small unmanned aircraft, personal watches, and light aircraft would all benefit from compact, inexpensive designs. Which antennas would be well suited to receive a given APNT signal? Addition and certification of antennas on aircraft can be costly. Future research might explore the possibility of using a single antenna for UAT communication at 978MHz and APNT reception at 971MHz.

A third area of future research focuses on pseudolite clock synchronization. As discussed in this thesis, TimeLoc via line-of-sight transmissions is not a viable solution. Technology exists that could potentially make satellite based time references a robust and viable option (Lo, Akos and Dennis, Time Source Options for Alternate Positioning, Navigation, and Timing (APNT) 2012). LocataLites (and UHARS pseudolites) rely on 1Hz updates of a GPS time reference at the Master pseudolite. Any error in the Master pseudolite's reference to true GPS or drift between updates is irrelevant to the positioning accuracy of the pseudolite network. Rather, positioning accuracy is dependent on the network's ability to synchronize clocks via TimeLoc. Modification of the LocataLite architecture to accurately synchronize each pseudolite independently to GPS or other GNSS should be explored. Pseudolite clock correction to better than 3ns would contribute less than a meter to URE. Based on signal performance estimates in this thesis, that is well within the performance margin provided.

Integrity is important attributes that should be further studied. Integrity in the GPS is partly inherent in the fact that it is space based, controlled and monitored by the DOD. Primarily, integrity is based on RAIM predictions and measurements. RAIM requires an over determined solution that is easily available from the GPS but would require a significant increase in the number of pseudolites installed over the CONUS. Methods to replace RAIM as the primary means of integrity checking should be researched by the APNT team. Increasing the data rate of the navigation message may allow for public key encryption. Monitoring of the ranging signal from each pseudolite and broadcasting an integrity flag on a separate channel is also a possibility.

Appendix

A. PNT Performance Requirements

		Precision-based Navigation, ADS-B Surveillance and Timing Performance In Support of Trajectory-based Operations								
			Navigation		**Surveillance**			**Positioning**		**Time Performance**
			(≥99.0% Availability)		(≥99.9% Availability)			GNSS PNT		RTP[1]
			Accuracy	Containment	Separation	NACp	NIC	(99.0 - 99.999%)		
Aircraft State	**Leader/ Follower**	**Flight Operation**	(95%)	(10^{-7})		(95%)	(10^{-7})			
1		**Parked**								
2		**Taxi-out**	Visual	Visual	Visual	0.05 nm (8)[2]	0.6 nm (6)[2]	GNSS		(+/-) 1 minute
		Low-vis (300-600 RV	1m	3m	1,200 feet[3]	121 m (8)	0.2 nm (7)	GNSS	GBAS	(+/-) 3 minutes[4]
		Low-vis (<300 RVR)	1m	3m	1,200 feet	121 m (8)	0.2 nm (7)	GNSS	GBAS	(+/-) 3 minutes
3,4		**Takeoff**	Visual	Visual	Visual	0.05 nm (8)	0.6 nm (6)	GNSS		(+5/-15) minutes
		High Density Airport	Visual	Visual	Visual	0.05 nm (8)	0.6 nm (6)	GNSS		(+/-) 1 minute
		Low-vis (300-600 RV	1m	3m	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS	GBAS	(+/-) 3 minutes[4]
		Low-vis (<300 RVR)	1m	3m	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS	GBAS	(+/-) 3 minutes[4]
5,13		**Climb to Cleanup**[6]	0.3 nm	0.6 nm	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS		(+/-) 1 minute
6,13	**x**	**Departure/Climb**	1 nm	2 nm	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS		(+5/-15) minutes
		Top of Climb	0.3 nm	0.6 nm	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS		(+5/-15) minutes
		High Density Airspace	0.3 nm	0.6 nm	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS		(+1/-5) minutes
		Top of Climb	0.3 nm	0.6 nm	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS		(+1/-5) minutes
		Top of Climb (Merge)	0.3 nm	0.6 nm	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS		(+/-) 1 minute[7]
7	**x**	**Cruise**[8]	10 nm	20 nm	20 nm	0.1 nm (7)	1 nm (5)	GNSS		(+/-) 2-5 minutes
			4 nm	8 nm	10 nm	0.1 nm (7)	1 nm (5)	GNSS		(+/-) 2-5 minutes
			2 nm	4 nm	5 nm	<308 m (7)	<1 nm (5)	GNSS		(+/-) 2-5 minutes
		High Density Airspace	1 nm	2 nm	3 nm[15]	<92.6 m (8)	<0.2 nm (7)	GNSS		(+/-) 1-3 minutes
8	**x**	**Top of Descent**	2 nm	4 nm	5 nm	<308 m (7)	<1 nm (5)	GNSS		(+/-) 3 minutes
		High Density Airspace	1 nm	2 nm	3 nm	<92.6 m (8)	<0.2 nm (7)	GNSS		(+1/-3) minutes
10	**x**	**Arrival**	1 nm	2 nm	3 nm	<308 m (7)	<1 nm (5)	GNSS		(+/-) 3 minutes
		High Density Airspace	0.3 nm	0.6 nm	3 nm	<92.6 m (8)	<0.2 nm (7)	GNSS	GBAS	(+/-) 30 seconds
11,12	**x**	**Approach**								(+/-) 30 seconds
		Initial Approach Fix								(+/-) 30 seconds
		Final Approach Fix								(+/-) 20 seconds
		Runway Threshold								(+/-) 20 seconds
		High Density Airports								
		Metering Fix								(+/-) 12-18 seconds
		Initial Approach Fix								(+/-) 20 seconds
		Stable Approach Point[9]								(+/-) 3-4 seconds
		Final Approach Fix								(+/-) 3-4 seconds
		Runway Threshold								(+/-) 3-4 seconds
14,15	**x**	**Single Runway**								
		LNAV	0.3 nm	0.6 nm	3 nm	0.05 nm (8)	0.6 nm (6)	GNSS	SBAS	
		RNP (AR)	0.3-0.1 nm[14]	0.3-0.1 nm[14]	3 nm	TBD[10]	TBD	GNSS	SBAS	
		LPV	16m/4m	40m/50m	3 nm	TBD	TBD	GNSS	SBAS	
		LPV-200	16m/4m	40m/35m	3 nm	TBD	TBD	GNSS	SBAS	
		GLS Cat-I	16m/4m	40m/10m	3 nm	TBD	TBD	GNSS	GBAS	
		GLS Cat-III	16m/4m	40m/10m	3 nm	TBD	TBD	GNSS	GBAS	
		High Density Airports								
14,15	**x**	**Parallel Runways**[11]								
		> 4,300 feet Separat	0.3 nm	0.6 nm	2 nm IPA[12]	0.05 nm (8)	0.6 nm (6)	GNSS	SBAS	
		3,400 - 4,300 feet	16m/4m	40m/10m	2 nm IPA	121 m (8)	0.2 nm (7)	GNSS	SBAS	
		2,500 - 3,400 feet	16m/4m	40m/10m	2 nm IPA	121 m (8)	0.2 nm (7)	GNSS	GBAS	
		1,600 - 2,500 feet	16m/4m	40m/10m	2.5 nm DPA	TBD	TBD	GNSS	GBAS	
		750 - 1,600 feet	16m/4m	40m/10m	2.5 nm DPA	TBD	TBD	GNSS	GBAS	
16		**Taxi-in**	Visual	Visual	Visual	0.05 nm (8)	0.6 nm (6)	GNSS		(+/-) 3 minutes
		Low-vis (300-600 RV	1m	3m	1,200 feet	121 m (8)	0.2 nm (7)	GNSS	GBAS	(+/-) 3 minutes
		Low-vis (<300 RVR)	1m	3m	1,200 feet	121 m (8)	0.2 nm (7)	GNSS	GBAS	(+/-) 3 minutes

Notes: 1. Required Time Performance (RTP) has been created by the JPDO TBO Study Team to represent performance goals ur
confirmed by research and represents a range of time values.
2. Navigation Accuracy Category for Position (NACp) and Navigation Integrity Category (NIC) values provided
Surveillance Integrity Level (SIL) in ( ).
3. Requires research. Assumes 20 nm/hour taxi speed and being able to detect another aircraft/vehicle by ADS-B
and stopping to avoid collision.
4. In low-vis conditions, capacity is reduced and RTP increases to compensate for slower surface movement.
5. Centerline guidance required for takeoff roll.
Operations <300 RVR are expected to be possible with enhanced vision that produces the equivalent of 300 RVR visibilit
6. Flight segment used to transition from liftoff to start of climb route where gear and flaps are retracted.
7. Increased precision in RTP required to merge into an overhead flow.
8. Includes oceanic and offshore operations.
9. Stable approach point is where the aircraft is fully configured and slowed to appropriate speed and the
pilot is prepared to land. In TBO, this is a point where time changes are not made.
10. Surveillance values dependent on research to mirror ADS-B In requirements for the procedure
11. TBO envisions 2,500 feet lateral runway separation to be an independed arrival stream and any less
runway spacing is a dependent arrival stream between the two runways
12. Independent Parallel Approach (IPA); Dependent Parallel Approach (DPA)
13. Operational requirements are defined for total system accuracy, which is dominated by flight technical error
and position accuracy for the operation is negligible.
14. Containment for RNP AR is specified as a total system requirement; value is representative of current approvals.
15. Assessment of approval for 3 nm separation for NACp 92.6 m and NIC <0.2 nm not yet completed (August 2011)

B. OI Shortfalls Listed

JPDO Identifier	Targeted NextGen Capability For 225	APNT Function	Impact	APNT Supported?	APNT Gap	Performance Zone	Name	Description	Benefits	Solution Set	Service
310		Provides position to GA aircraft for ADS-B positioning for more direct routing through busy terminal area airspace	1	2	Cost may prohibit acces to GA	3	Improved GA Access to Traverse Terminal Areas	This Operational Improvement (OI) results in increased access to busy airspace, such as Class B, for General Aviation (GA) operators. More direct routing for GA operators is facilitated through improved access to traverse busy terminal area airspace via the continued use and possible expansion of Visual Flight Rules (VFR) Flyways as well as by the utilization of Automatic Dependent Surveillance-Broadcast (ADS-B) technologies. Typically, GA operators have to fly "around" busy airspace, with associated penalties in efficiency. With this OI a GA flight is more likely to transit through busy airspace when the desired flight path crosses that airspace. Major benefits are access and efficiency. This OI primarily affects arrival/departure airspace and En Route airspace. Roles/Responsibilities: Based on the initial planned solution (static corridors), there are no changes in roles/responsibilities.	Increased efficiency Increased accessibility Enhanced user-preferred trajectories	Increase Flexibility in the Terminal Environment	ATC-Separation Assurance

311		Provides position to continue RNAV and RNP to continue more efficient aircraft trajectories for repeatable and predictable navigation	1	2	d	1,3	Increase Capacity and Efficiency Using Area Navigation (RNAV) and Required Navigation Performance (RNP)	Both RNAV and RNP will enable more efficient aircraft trajectories. RNAV and RNP combined with airspace changes, increase airspace efficiency and capacity. RNAV and RNP will permit the flexibility of point-to-point operations and allow for the development of routes, procedures, and approaches that are more efficient and free from the constraints and inefficiencies of the ground-based NAVAIDS. This capability can also be combined with an Instrument Landing System (ILS), to improve the transition onto an ILS final approach and to provide a guided missed approach. Consequently, RNAV and RNP will enable safe and efficient procedures and airspace that address the complexities of the terminal operation through repeatable and predictable navigation. These will include the ability to implement curved path procedures that can address terrain, and noise-sensitive and/or special-use airspace. Terminal and en route procedures will be designed for more efficient spacing and will address complex operations.	* Improved efficiency	Initiate Trajectory Based Operations	Airspace Management

317		Will provide position to enable navigation to navigate to ILS final approach course and missed approach procedures	2	2	RNP .3 not sufficient to maintain 2025 capacity in Terminal Environment, ILS required	3	Low Visibility/Ceiling Approach Operations	The ability to complete approaches in low visibility/ceiling conditions is improved for aircraft equipped with some combination of navigation derived from augmented GNSS or ILS and other cockpit-based technologies or combinations of cockpit-based technologies and ground infrastructure. The ability to complete approaches in low visibility/ceiling conditions is improved for aircraft equipped with some combination of navigation derived from augmented GNSS or ILS and Head-up Display (HUD), EFVS, SVS, advanced vision system and other cockpit-based technologies that combine to improve human performance. Cockpit-based technologies allow instrument approach procedure access with reduced requirements on ground-based navigation and airport infrastructure. Due to onboard avionics airport access is maintained in low visibility/ceiling conditions.	To Be Determined	Increase Flexibility in the Terminal Environment	Navigation

327	x	Provides position information for ADS-B in real time for surveillance and automation.	2	1	Not provided on surface	S	Full Surface Traffic Management with Conformance Monitoring	Operational Improvement	Increased airport efficiency Enhanced surface safety Improved shared situational awareness Decreased emissions and airport noise levels	Increase Arrivals/Departures at High Density Airports	TM-Synchronization
330		Provide position to ground based automation to provide conflict free time based metering solutions	1	1	RNP .3 not sufficient to maintain 2025 capacity in Terminal Environment	3, S	Time-Based Metering in the Terminal Environment	Aircraft are time-based metered inside the terminal environment, enhancing efficiency through the optimal use of terminal airspace and surface capacity. ANSP automation develops trajectories and allocates time-based slots for various points (as needed) within the terminal environment, applying RNAV route data and leveraging enhanced surveillance, data communications, and closely spaced parallel, converging, and intersecting runway capabilities (where applicable). This OI extends current metering capabilities into the terminal environment and furthers the pursuit of end-to-end metering and trajectory-based operations. It also supports capabilities designed to expand the use of terminal separation standards in transition airspace.	Increased Efficiency Increased Capacity	Increase Arrivals/Departures at High Density Airports	TM-Synchronization

331	x	Provides position to update Metroplex scheduling automation to optimize runway and surface movement	2	2	Not provided on surface	3, S	Improved Management of Arrival/Surface/Departure Flow Operations	This Operational Improvement (OI) integrates advanced Arrival/Departure flow management with advanced Surface operation functions to improve overall airport capacity and efficiency. Air Navigation Service Provider (ANSP) automation uses arrival and departure-scheduling tools and four dimensional trajectory (4DT) agreements to flow traffic at high-density airports	Improved efficiency Reduced fuel burn, airport noise, and emissions	Increase Arrivals/Departures at High Density Airports	TM-Synchronization
334		Provides position to equipped aircraft onboard displays and alerting systems for independent converging runways to continue VMC departure and arrival rates	2	2	RNP .3 not sufficient to maintain 2025 capacity in Terminal Environment if ILS is required	3	Independent Converging Approaches in IMC	This Operational Improvement (OI) enables maintaining Visual Meteorological Condition (VMC) arrival and departure rates in Instrument Meteorological Conditions (IMC) through use of onboard displays and alerting for independent converging runways. Using precision navigation, cooperative surveillance, and onboard algorithms and displays allows the reduction of lateral separation requirements for converging runway operations in IMC. Includes independent approaches to converging runways that are centerline distances greater than 2500 ft. The implementation of this OI is strongly dependent on when an airline decides this is important and steps forward to advocate for it.	0	Increase Flexibility in the Terminal Environment	ATC-Separation Assurance

340	x	Provides position to ADS-B for self separation. Accuracy and timeliness is improved over traditional surface MLAT.	2	1	Not provided on surface	S	Provide Surface Situation to Pilots, Service Providers and Vehicle Operators for Near-Zero-Visibility Surface Operations	Aircraft and surface vehicle positions are displayed to aircraft, vehicle operators, and air navigation service providers (ANSP) to provide situational awareness in restricted visibility conditions, increasing efficiency of surface movement. Surface movement is guided by technology such as moving map displays, enhanced vision sensors, synthetic vision systems, Ground Support Equipment and a Cooperative Surveillance System. Aircraft and surface vehicle position will be sensed and communicated utilizing systems such as Cockpit Display of Traffic Information (CDTI) and Automatic Dependent Surveillance-Broadcast (ADS-B)	Improved situational awarenessEnhanced safetyEnhanced efficiency	Increase Flexibility in the Terminal Environment	ATC-Separation Assurance
341	x	Provides position to ADS-B for self separation. Accuracy and timeliness is improved over traditional surface MLAT.	2	1	Not provided on surface	S	Limited Simultaneous Runway Occupancy	Runway capacity is increased through the allowance of more than one aircraft on the runway, at a given time, for specific situations. The expected use is to relax some of the present procedures/rules, thereby allowing an aircraft to land while another aircraft is in the process of exiting the runway onto a taxiway, or allowing an aircraft to enter the runway while another aircraft is in the process of departing from that runway.	Increased capacity	Increase Arrivals/Departures at High Density Airports	ATC-Separation Assurance

348	x	Provides required performance criteria for less than 3 mile separation standards in dense terminal areas	1	1	RNP .3 not sufficient to support <3 nm separation	3	Reduce Separation - High Density Terminal Less Than 3-miles	Metroplex airspace capacity is increased through implementing separation procedures for conducting separation with less than 3-miles between arrival and departure routes in a high density environment. This Operational Improvement increases metroplex airspace capacity and supports super density airport operations. Enhanced surveillance and data processing provides faster update rates to allow reduced separation.	Increased capacity	Increase Arrivals/Departures at High Density Airports	ATC-Separation Assurance
359	x	Provides position to ADS-B for self separation	1	1	Solution alternatives do not support Oceanic service	1	Self-Separation Airspace - Oceanic	Oceanic user efficiency and Air Navigation Service Provider (ANSP) productivity are improved through self-separation operations in designated oceanic airspace for capable aircraft.	Increased efficiency	Initiate Trajectory Based Operations	ATC-Separation Assurance
363	x	Provides position for equipped aircraft for merging, passing or crossing of other traffic. Provides	1	2	RNP .3 not sufficient to maintain 2025 capacity in Terminal Environment if ILS is required	1,3	Delegated Separation - Complex Procedures	In Air Navigation Service Provider (ANSP)-managed airspace, the ANSP delegates separation responsibilities to capable aircraft to improve operator routing, enhance operational efficiency, or increase ANSP productivity.	Increased efficiency	Increase Arrivals/Departures at High Density Airports	ATC-Separation Assurance

		position for conflict detection and alerting									
383		Provides position to ADS-B. Accuracy and timeliness is improved over traditional surface MLAT.	1	1	Not provided on surface	3, S	Improved Runway Safety Situational Awareness for Controllers	At large airports, current controller tools provide surface displays and can alert controllers when aircraft taxi into areas where a runway incursion could result. Additional ground-based capabilities will be developed to improve runway safety that include expansion of runway surveillance technology (i.e., ASDE-X) to additional airports, deployment of low cost surveillance for medium-sized airports , improved runway markings, and initial controller taxi conformance monitoring capabilities. These ground-based tools will provide a range of capabilities to help improve runway safety for medium- to large-sized airports.	*Increased safety	Increase Flexibility in the Terminal Environment	ATC-Advisory

384	x	Provides position to ADS-B for self separation. Accuracy and timeliness is improved over traditional surface MLAT.	2	1	Not provided on surface	3,S	Improve Runway Safety Situational Awareness for Pilots	Runway safety operations are improved by providing pilots with improved awareness of their location on the airport surface as well as runway incursion alerting capabilities. To help minimize pilot disorientation on the airport surface, a surface moving map display with ownship position will be available. Both ground-based (e.g., RWSL) and cockpit-based runway incursion alerting capabilities will also be available to alert pilots when it's unsafe to enter the runway.	*Increased safety	Increase Flexibility in the Terminal Environment	ATC-Advisory
386		Provides position in mountainous areas where radar coverage is limited for both navigation and surveillance	1	2	APNT CONOPs only supports 135 busiest airports, RADAR like coverage not available below 5000'AGL	3	Expanded Radar-like Services to Secondary Airports	Expanded capacity is available in Instrument Meteorological Conditions (IMC) at additional secondary airports. Expanded delivery of radar-like coverage with surveillance alternatives such as Automatic Dependent Surveillance-Broadcast (ADS-B) coverage, combined with other radar sources, and with an expansion of communication coverage provides equipped aircraft with radar-like services to secondary airports. Equipped aircraft automatically receive airborne broadcast traffic information. Surface traffic information is also available at select non-towered satellite airports. Enhanced surveillance	Improved safety Expanded ANSP services Enhanced surveillance coverage Enhanced search and rescue coordination	Increase Flexibility in the Terminal Environment	ATC-Separation Assurance

								coverage in areas of mountainous terrain where radar coverage is limited, especially to small airports, enables ANSP to provide radar-like services to equipped aircraft. This capability enhances alerting and emergency services beyond normal radar coverage areas.			
388		Provides position for a transition from localizer guidance to climb navigation for turning procedures (SIDS)	2	1	Not provided on surface	3, S	Low Visibility/Ceiling Takeoff Operations	Leverages some combination of HUD, EFVS, SVS, or advanced vision system capabilities to allow appropriately equipped aircraft to takeoff in low visibility conditions. Due to onboard avionics the aircraft will be less dependent on ground based infrastructure at the airport while conducting take-off operations. Currently, visibility minimums for takeoff are dependent on aircraft equipment, ground infrastructure, and runway marking and lighting. This ensures that pilots are able to visually maintain the runway centerline during both nominal and aborted takeoffs. By using cockpit-based technologies such as HUD, EFVS, SVS or other advanced vision system technologies, the pilot will be able to maintain an equivalent awareness of runway centerline with reduced dependence on airport	*Increased Access	Increase Flexibility in the Terminal Environment	Navigation

								infrastructure when visual conditions are below those normally required for takeoff.			
389		Provides course and altitude guidance to touchdown as well as runway situational awareness	2	2	RNP .3 not sufficient to maintain 2025 capacity in Terminal Environment. Not supported if ILS is not available.	3, S	Low Visibility/Ceiling Landing Operations	The ability to land in low visibility/ceiling conditions is improved for aircraft equipped with some combination of navigation derived from augmented GNSS or ILS and other cockpit-based technologies or combinations of cockpit-based technologies and ground infrastructure.The ability to land in low visibility/ceiling conditions is improved for aircraft equipped with some combination of navigation derived from augmented GNSS or ILS, and Head-up Display (HUD), EFVS, SVS, advanced vision system and other cockpit-based technologies that combine to improve human performance. Cockpit-based technologies allow instrument approach procedure access with reduced requirements on ground-based navigation and airport infrastructure. Due to onboard avionics airport access is maintained in low visibility/ceiling conditions.	*Increased Safety*Increased Access	Increase Flexibility in the Terminal Environment	Navigation

390		Provides position for RNP/RNAV SIDS to enable aircraft to avoid hazards.	2	2	RNP .3 not sufficient to maintain 2025 capacity in Terminal Environment	3	Low Visibility/Ceiling Departure Operations	Leverages augmented GNSS capabilities to allow appropriately equipped aircraft to depart in low visibility conditions. Due to onboard avionics the aircraft will be able to depart in low visibility conditions using RNAV/RNP SIDs, EFVS, SVS, or advanced vision systems.	*Increased access *Enhanced Safety	Increase Flexibility in the Terminal Environment	Navigation
409	x	Provides postion to ADS-B for use at airports without ground based surveillance	2	2	APNT CONOPs only supports 135 busiest airports, RADAR like coverage not available below 5000'AGL	3, S	Remotely Staffed Tower Services	Remotely Staffed Towers provide ATM services for operations into and out of designated airports without physically constructing, equipping, and/or sustaining tower facilities at these airports. Instead of out-the-window visual surveillance, controllers maintain situational awareness provided by surface surveillance displayed on an ANSP display system and a suite of decision support tools using aircraft-derived data.	*Increased airport capacity in low visibility and night conditions *Improvement in runway incursion alerting *Improvement in availability and performance of ATM services at airports *Reduced cost of sustaining, expanding, and improving ATM services at airports	Transform Facilities	Infrastructure-Information Management Service

6005		Provides navigation capability to remain on planned optimized route to reduce emissions, fuel burn and noise	2	2	RNP .3 not sufficient to maintain 2025 capacity in Terminal Environment. Negated if ILS is not optimal approach.	All	Environmentally & Energy Favorable Air Traffic Management Concepts and Gate-to-Gate Operational Procedures - Phase II	Explore, develop, demonstrate, evaluate and support the implementation and deployment of Air Traffic Management and gate-to-gate operational changes to the NAS that have the potential to reduce the environmental impacts of aviation support mobility growth by increasing the capacity and throughput of the NAS. It will include multiple increments delivered over time.	No Benefits Provided	Increase Safety, Security, and Environmental Performance	Infrastructure-Information Management Service
6022		Provides navigation capability to remain on planned optimized route to reduce emissions, fuel burn and noise	2	2	RNP .3 not sufficient to maintain 2025 capacity in Terminal Environment. Negated if ILS is not optimal approach.	All	Environmentally & Energy Favorable Air Traffic Management Concepts and Gate-to-Gate Operational Procedures - Phase III	Explore, develop, demonstrate, evaluate and support the implementation and deployment of Air Traffic Management and gate-to-gate operational changes to the NAS that have the potential to reduce the environmental impacts of aviation support mobility growth by increasing the capacity and throughput of the NAS. It will include multiple increments delivered over time.	No Benefit Provided	Increase Safety, Security, and Environmental Performance	Infrastructure-Information Management Service

		Provides postion to ADS-B for separation as well as continuous updates to INS and other navigation	2	1	Solution alternatives do not support Oceanic service	1	Oceanic In-trail Climb and Descent	ANSP automation enhancements will take advantage of improved communication, navigation, and surveillance coverage in the oceanic domain. When authorized by the controller, pilots of equipped aircraft use established procedures for climbs and descents. Improved ANSP automation provides the opportunity to use new procedures and reduce longitudinal spacing for the duration of the procedure. Aircraft are able to fly the most advantageous trajectories with climb and descent maneuvers.	Improved efficiency Increased capacity Reduced fuel burn and engine emissions	Initiate Trajectory Based Operations	ATC-Separation Assurance

C. Glossary of Acronyms

3D RMS:	Three Dimensional Root Mean Squared
4DT:	Four Dimensional Trajectory
ADS-B:	Automatic Dependent Surveillance – Broadcast
ADS-R:	Automatic Dependent Surveillance – Re-broadcast
AGL:	Above Ground Level
ANSP:	Air Navigation Service Provider
APNT:	Alternate Precision Navigation and Timing
ARNS:	Aeronautical Radio Navigation Service
ATC:	Air Traffic Control
ATCRBS:	Air TrafficControl RADAR Broadcast Service
CDMA:	Code Division Multiple Access
CFR:	Code of Federal Regulations
CONOPS:	Concept of Operations
CONUS:	Continental United States
CPFSK:	Continuous Phase, Frequency Shift Keying
DLL:	Delay Lock Loop
DME:	Distance Measuring Equipment
DOP:	Dilution of Precision
DS-BPSK:	Direct Sequence – Bi-phase Shift Keying
FAA:	Federal Aviation Administration
FCC:	Federal Communications Commission
FIS-B:	Flight Information Service - Broadcast
GBT:	Ground Based Transmitter
GNSS:	Global Navigation Satellite System
GPS:	Global Positioning System
HPE:	Horizontal Position Error
ICAO:	International Civil Aviation Organization
ICD:	Interface Control Document
IFR:	Instrument Flight Rules
ILS:	Instrument Landing System
IMC:	Instrument Meteorological Conditions
JPDO:	Joint Planning Development Office
JTIDS:	Joint Tactical Information Distribution System
MLAT:	Multi-Lateration
MSO:	Message Start Opportunity
NAC:	Navigational Accuracy Code
NACp:	Navigational Accuracy Code for Position
NAS:	National Airspace
Next Gen:	Next Generation Airspace
OI:	Operational Improvement
OV:	Operational View
PDOP:	Positional Dilution of Precision

PRN:	Pseudo Random Noise
RAIM:	Receiver Autonomous Integrity Monitoring
RNAV:	Area Navigation
RNP:	Required Navigation Performance
SA:	Situational Awareness
SSA:	Shared Situational Awareness
SV:	System View
TACAN:	Tactical Aerial Navigation
TBO:	Trajectory Based Operations
TDMA:	Time Division Multiple Access
TIS-B:	Traffic Information Service - Broadcast
UAT:	Universal Access Transceiver
UHARS:	Ultra High Accuracy Reference System
URE:	User Range Error
VOR:	VHF Omnidirectional Ranging
VOR MON:	VOR Minimum Operating Network
WAAS:	Wide Area Augmentation System

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14. ABSTRACT
By 2025 the FAA plans to have fully implemented its NextGen Airspace design. NextGen takes advantage of modern positioning technologies as well as automation, data sharing, and display technologies that will allow more efficient use of our ever busier National Airspace (NAS). A key element of NextGen is the transition from surveillance RADAR providing aircraft separation and navigation to the use of the GPS and Automatic Dependent Surveillance Broadcast (ADS-B). ADS-B couples the precision of the GPS with networked ground and airborne receivers to provide precise situational awareness to pilots and controllers. The result is increased safety, capacity, and access with reduced reliance on an outdated and costly existing infrastructure. Reliance on the vulnerable GPS requires a backup system with higher positioning accuracy than those that are in place today. The USAF 746th Test Squadron at Holloman AFB, in partnership with Locata Corp., has demonstrated an Ultra High Accuracy Reference System (UHARS) over the Holloman Range composed of pseudolites (ground based satellites) transmitting GPS like signals. This study evaluates the suitability of the UHARS when applied on a national scale to meet Alternate Precision Navigation and Timing (APNT) requirements. From a systems architecture perspective UHARS is evaluated against APNT CONOPs stated Operational Improvements and Scenarios. From a signal architecture perspective the UHARS is evaluated against frequency and bandwidth constraints, service volume requirements and positioning accuracy determined by NextGen Airspace aircraft separation criteria.

15. SUBJECT TERMS
Alternate Precision Navigation Timing, APNT, Locata, NextGen, Next Generation Airspace

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